Arnold Schwarzenegger
Governor

TRACKING THE SUN FOR HIGH-VALUE GRID ELECTRICITY

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Tracking the Sun for High-Value Grid Electricity Final Report is the final report for the Tracking the Sun for High-Value Grid Electricity project (500-03-035) conducted by PowerLight. The information from this project contributes to PIER's Energy Research and Development program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

This report outlines work performed to improve the reliability and reduce installation time, maintenance time, and capital costs of PowerLight's ground- mounted solar tracking system for utility and other large-scale commercial applications known as PowerTracker. To achieve these goals, PowerLight worked to improve all aspects of the product, including the drive unit and controller, design tools, structural design, documentation, certifications, and electrical system design. As a result of the work performed under this contract, significant improvement in each of the targeted areas was achieved. Highlights include the implementation and deployment of a new controller, advances in structural design and wind load calculations, new construction practices, and a detailed product installation manual. Nearly all of the advances made under the contract have been or are in the process of being commercialized, with the ultimate effect of reducing the overall cost of solar electricity for PowerLight's customers specifically and for the solar market in general. The improved tracker will benefit California by enabling installation of more solar plants in the state several large-scale solar plants have been already built in California using this tracker. These plants have increased the generation of clean renewable energy in the state, which will help the state meet its renewable portfolio standard (RPS) goals. The tracker will help PowerLight Corporation grow its solar business in United States as well as globally, which in turn will help the economy and create more green jobs in California.

Keywords: Solar, photovoltaic, PV cells, PV panels, tracking systems, electricity production, distributed generation

Executive Summary

Introduction

The PowerTracker design represents a breakthrough in solar tracking systems by allowing a large number of photovoltaic (PV) modules up to 250 kilowatt-peak to be actuated with a single motor and controller. For minimal incremental cost of the controller and actuator, 15 percent to 35 percent more energy is produced compared to a stationary array using the same number of photovoltaic modules.

Purpose

This project is to improve the reliability and reduce installation time, maintenance time, and capital cost of the PowerTracker system for utility and other large-scale commercial applications.

Objectives

The following specific measures for this project include:

- Reduce PowerTracker life cycle cost.
- Reduce cycle time from system design to installation.
- Improve reliability and durability.
- Reduce steel waste stream.

Project Outcomes

This effort has improved single-axis PV tracking technology by increasing the quality while driving costs down, leading to the creation of more renewable options for California energy consumers. To achieve these goals, PowerLight adopted a holistic approach to product improvement. As such, this contract covered the full range of activities related to ground mounted solar tracking systems, including:

- The drive unit and controller
- Tools for design automation and performance analysis
- Tracker structural design
- Documentation and product certifications
- Electrical system design

Conclusions and Recommendations

As a result of this contract, significant improvement in each of the targeted areas was achieved. A new controller design was implemented and has been deployed in the field with no reported reliability problems thus far. Improvements were made to both PowerLight's performance analysis and design tools, reducing the time required to analyze, design, and install individual PowerTracker projects by up to 58 percent. Important advances in structural design allowed lower cost and higher reliability trackers to be constructed, driven in part by new construction practices and a better understanding of wind loading. Based on current projects, PowerLight has achieved a 19 percent decrease in life cycle costs and anticipates an additional 10 percent savings due to decreased operations and maintenance expenses. In addition, PowerLight developed a new foundation design, resulting in a 20 percent reduction in steel waste streams for projects installed in 2006; all remaining steel waste is recycled. Thorough and detailed product documentation has been extremely well received by system installers both inside and outside PowerLight, providing the tangible benefit of standardizing installation practices and thus improving product consistency.

1.0 Introduction

Figure 1-1. PowerTracker system installation
Photo Credit: PowerLight Corporation

Single-axis trackers have been used productively in photovoltaic systems since the early 1980s. The first large-scale one-axis system – still operating – was a 1 megawatt (MW) system installed by the Sacramento Municipal Utility District at Rancho Seco in 1984. The obvious advantage of one-axis tracking is that 15 percent to 35 percent more energy is produced compared to a stationary array using the same number of photovoltaic modules. Despite this advantage, single-axis trackers enjoyed relatively little market development until the late 1990s because, until that time, the best available commercialized technology was expensive and unreliable. The technology was expensive because separate motor/drive/controllers, or multiple passive actuators, were required for each mechanical row of photovoltaic modules, adding roughly one dollar per watt installed cost and thus negating much of the benefit from increased energy production. As a result, customer demand was low.

In 1999, Shingleton Design, LLC, developed and introduced the MaxTracker – a single-axis tracker with the potential for low cost and high reliability. This design was literally an application breakthrough. Using a simple mechanical linkage, a single motor/drive/controller could track up to 24 rows – more than 150 kilowatt (kW) – of photovoltaic at one time. With this technology, a customer can reliably track the sun for about the same cost as installing a fixed array. From 1999 to 2003, 6.7 MW of MaxTrackers were installed in the United States, with more than 2 MW installed in California alone. By contrast, less than 4 MW of all competing, one-axis tracker technologies have been installed over the 20 year period of 1984 to 2003. In 2002, PowerLight Corporation acquired ownership of the MaxTracker design, which was subsequently renamed the PowerTracker® system.

The PowerTracker structure, covered by US Patent No. 6058930 with additional patents pending, consists of high strength steel torque tubes and support posts, an industrial drive system, controller bearings and fasteners. The parts count has been kept low to minimize inventory and procurement costs. For any given project, a combination of these components are arranged to the system specific characteristics, including the number of PV modules, the module type and size, the design wind speed, seismic and soil conditions, and the site configuration. Although the basic components are simple, many sites require custom engineering and design elements that add extra costs and delivery time.

1.1 Problem Statement

While the PowerTracker platform is the leading single-axis tracker technology, there are still significant opportunities to improve the product and make it more viable to California energy consumers through cost reduction and reliability improvements. The existing system is expensive and complex to install due to some non-standardized elements in the structural and electrical design. Maintenance costs are also high due to the relatively low reliability of the antiquated controller technology and the specialized skills required servicing these controllers adequately. Furthermore, existing design software does not specifically address single-axis tracker parameters, which results in longer system design lead times. Capitalizing on these opportunities is the objective of this project, which was accomplished through performance of the following tasks:

- Development of next-generation controller and drive systems
- Improvement of software design and simulation tools
- Development of next-generation structural designs
- Development of documentation and certification
- Development of next-generation electrical designs

The successful execution of these tasks has reduced delivered systems costs and improved overall system quality and reliability.

2.0 Project Objectives

2.1 Relationship to PIER Goals

This agreement meets the PIER goal of improving the reliability, quality, and sufficiency of California's electricity by improving on existing PV tracking technology. This project also meets the secondary PIER goal of providing greater choices for California consumers by improving available solar technologies and making them more cost effective.

2.2 Project Goals

The goal of this project is to improve the PowerTracker product by making it more reliable and cost-effective for the California consumer.

2.3 Objectives

The objectives of this project are to improve the reliability and reduce installation time, maintenance time and capital costs of the PowerTracker system for utility and other large-scale commercial applications. The following specific measures for this project include the following:

- Reduce PowerTracker life cycle (design, installation, construction, and operation) costs by 36 percent.
- Reduce cycle time from system design to installation by 40 percent.
- Improve reliability and durability such that unscheduled maintenance will be reduced an estimated 65 percent.
- Reduce steel waste stream by 70 percent and show substantially less environmental impact for manufacturing, construction, and operations.

This effort has improved single-axis PV tracking technology by increasing the quality while driving costs down, leading to the creation of more renewable options for California energy consumers.

3.0 Project Approach

This project consists of the following six tasks geared toward the overall improvement of the PowerTracker technology:

Task	Description
Task 1	Administration
Task 2	Controller and Drive Improvements
Task 3	Design Tool Improvements
Task 4	Next Generation Structural Design
Task 5	Documentation and Certification
Task 6	Next Generation Electrical Design

The approach to each technical task (Tasks 2-6) is described in the sections that follow.

For reference, the following figures depict a representative 125-kW PowerTracker array layout (Figure 3-1) and a detail of the main system components (Figure 3-2).

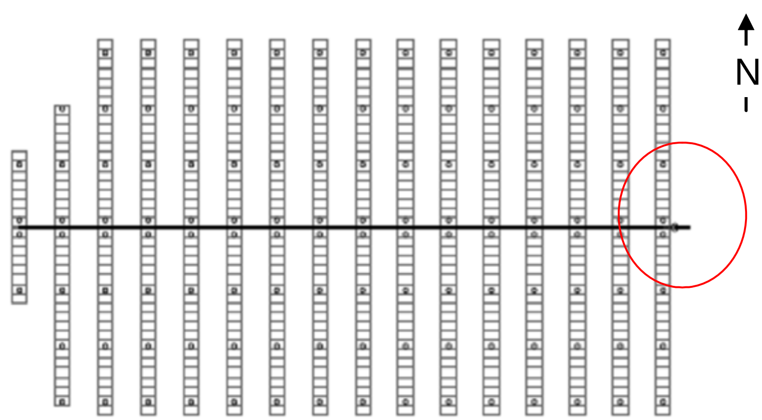

Figure 3-1. 125-kW PowerTracker array.
Source: PowerLight Corporation

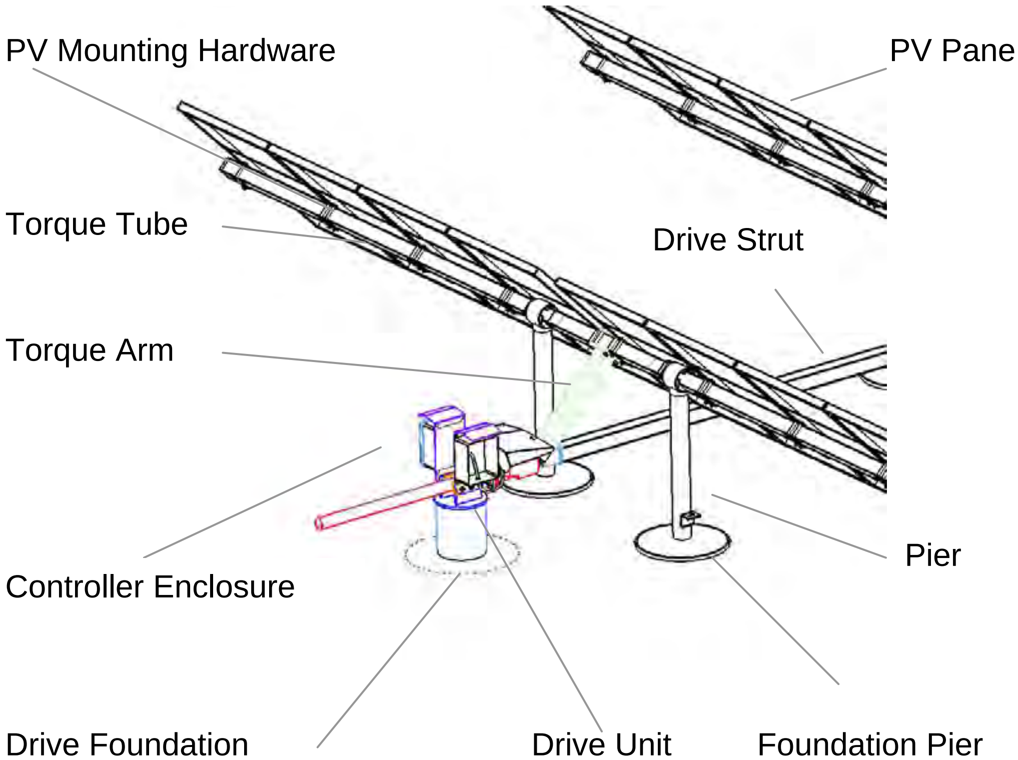

Figure 3-2. PowerTracker system components

Source: PowerLight Corporation

3.1 Task 2: Controller and Drive Improvements

The drive unit is composed of a motor, linear actuator, and controller that set the angle of the PV array to maximize the solar energy collected at any particular time and date. While the PowerTracker system design minimizes the cost of electricity impact from the drive unit and controller by using it to actuate a very large number of PV modules, the cost of these components remains non-trivial. Further, the labor costs associated with commissioning, operating, and maintaining the drive unit and controller portion of an array is substantial.

The primary goal of Task 2 is to reduce the direct cost associated with the drive unit and controller while increasing its reliability and performance. The following subsections detail the goals and approach for each specific activity performed to achieve the overall goals for Task 2.

3.1.1 Controller Specification

A detailed specification for the requirements and features of the improved drive unit and controller was developed. The goal of this activity was to focus the design effort from the start on activities that contribute directly to delivering lower cost and improved performance. Without a detailed specification, development costs would likely have been higher as design effort could have been spent on items that were not required for the product. A specification also contributes to reliability and performance by allowing a better organized design since the interdependencies are understood in advance.

3.1.2 Use of Off-the-Shelf Components

Unlike prior systems, the controller developed under this project is consists exclusively of industrial off-the-shelf components. This approach allows PowerLight to leverage the cost structure, reliability, and performance of existing technology while reducing design time and resource usage. A custom solution is also not likely to generate enough volume to generate economies of scale needed to reduce cost significantly.

3.1.3 Expanded Controller Capabilities and Functionality

To achieve the goals of lower total cost and higher reliability, some new capabilities and functionality were defined. These included the incorporation of a global positioning system (GPS) receiver to improve solar tracking performance and inclusion of a variable frequency drive (VFD) for more precise and reliable motor control, among others. The details of how these components improve the cost and performance of the controller are given in the corresponding results section.

3.1.4 Improved Feedback System

Due to prior performance and reliability problems with the potentiometer used for tilt angle feedback, a new measurement technique was desired. As a result, a solid state inclinometer was incorporated into the system. A solid state sensor is inherently more reliable than a mechanical potentiometer and thus helps to reduce maintenance and operating costs.

3.1.5 Upgraded Configuration Software Interface

One approach to reducing costs associated with the system commissioning process was to improve the controller user interface, which is the primary means by which new systems are configured for proper operation. The improved system can run on any Windows-based computer, but typically is used on a laptop computer by field technicians. The use of a well designed user interface not only reduces commissioning time and cost, but also reduces the likelihood of configuration errors that lead to a reduction in performance and recurring maintenance costs.

3.1.6 Installation Tooling

Imprecise installation of PowerTracker components can lead to both higher commissioning costs and long-term reliability problems. In particular, because of both the large scale of PowerTracker systems and the nature of field construction, precise placement of the drive unit can be somewhat variable. PowerLight's approach to addressing this problem was to design tooling to improve the precision and accuracy of controller placement during field installation.

3.1.7 Prototyping

Anytime a new product is introduced, there is some risk that design errors or other problems could emerge after the product is in the field. Given PowerLight's goal to reduce operating and maintenance costs through improved reliability, prototype driven units and controllers were developed. This approach mitigates the risk associated with a new product release by providing units that can be used for validation and testing purposes. Prototype units were tested in PowerLight's R&D lab in conjunction with testing on structural elements designed under Task 4. Details of the prototype design are included in the Project Outcomes section of this report.

3.1.8 Commercial demonstration

To validate the final design in a real world application, the controller was designed into and installed as part of a commercial system developed by PowerLight for an external customer. The results of this field trial were positive, indicating that the drive unit and controller design were successful in achieving the goals set forth as part of this contract. As of the writing of this report, the new drive unit and controller have been deployed successfully in three commercial systems, in California, with many other under construction or nearing completion on a global scale. More detail and performance data for the field trials are provided in the Project Outcomes section.

The following table lists the existing installations of the new controller along with basic project information.

Table 1. Commercial Demonstration Sites for Controller Assemblies

Project Name	Location	System Size (kWp)	No. of Controllers
Alameda Public Works	Hayward, CA	252	2
USPS San Francisco	San Francisco, CA	205	1
Napa Valley College	Napa, CA	1,157	5

Source: PowerLight Corporation

3.2 Task 3: Design Tool Improvements

Accurately predicting the energy production of various photovoltaic designs in a variety of locations is an important tool for buyers and system designers. It allows designers to understand the impact of various design changes on energy production. Current software programs to estimate the energy production of photovoltaic systems do not have the necessary functionality to simulate the output of modern single-axis tracker designs accurately, as important parameters are not accounted for in the model.

The goal of this task is to develop software tools to predict tracker system performance under a wide variety of site conditions. These tools allow for a performance comparison between fixed arrays and single-axis trackers. In addition, these tools aid in determining the distance between modules and module orientation for each installation site.

The approach taken to address the goals of Task 3 is discussed below.

3.2.1 Software Selection

PowerLight reviewed 10 photovoltaic energy simulation programs (Table 2). A set of selection criteria was developed to select the best software application to model the performance of PowerLight's grid-connected PowerTracker.

Table 2. Software candidates for evaluation

Software	Developer
Grennius 2.0	German Research Institute for Aviation and Space Travel
Homer	National Renewable Energy Laboratory
Insel 7.0	University of Oldenburg
PV-Design Pro 7.0	Maui Solar Energy Software Corporation
PV F-Chart	University of Wisconsin
PVS 2000	Fraunhofer ISE and Econzept Gmbh
PVSol	Valentin Energiessoftware
PVSYST 4.0	University of Geneva
Solar Pro	Laplace System Co. Inc
PVGrid 8.0 / PVForm	Sandia National Laboratories and Howard Wenger

Source: PowerLight Corporation

The following set of criteria was used to evaluate the potential software candidates. Each was measured against these criteria to find the one best suited for the research team's needs. The specific criteria are as follows:

Extent of Meteorological Data

The most important factor in photovoltaic energy simulation is the selection of meteorological data. Therefore, it is important that the program can import standard data from a variety of sources. In the United States, the most common data source is the TMY2 (Typical Meteorological Year 2) data set published by the National Renewable Energy Laboratory. In Europe, Satel-Light and the DoDa databank are typically used for energy simulations. Meteonorm is the most comprehensive database and includes data from all over the world. In order to model energy output, it is important that the program can import data from each of these sources.

Variety of Photovoltaic System Designs and Configurations

The ability to model a variety of designs and configurations is an important factor in modeling energy production and optimizing designs. A program needs to be able to model a single-axis tracker, as well as flat and tilted designs, at different azimuth angles to be able to select the best design for a given location. It is important to have the same application model for each design so that they can be compared and optimized without introducing differences in modeling methodologies.

Enter and Modify Component Data

The ability to model each design component of a photovoltaic system is another important factor in providing an accurate estimate of energy production. The ability to edit component data also allows for comparison of different technologies and balance-of-system components in order to optimize photovoltaic design. It is important for the user to be able to import and edit all relevant PV module characteristics, inverter characteristics, transformers, wiring design, and auxiliary loads.

Open Source Code–Ability to modify and improve algorithms

The ability to modify source code and improve algorithms based on new designs and measured performance data is an important factor in selecting the best simulation program.

Model Validation

The length of time a program has been in use and the validation of results against measured performance data are important factors in determining the accuracy of the energy prediction. To ensure accuracy it is important to use applications that have been in use for at least five years and that have been validated against several hundred operating photovoltaic systems.

Selection Results

PowerLight selected PVGrid 8.0 as the foundation for energy prediction simulations. PVGrid is based on a software package called PVForm, developed by Sandia National Laboratories and in use since 1988. Energy predictions have been validated against hundreds of operating PV systems. This software has the ability to use any TMY weather file, and users can edit all design components. In addition, the program can also simulate a variety of design configurations including flat, tilted, and tracking PV systems.

3.2.2 Software Modifications

PowerLight added several new functions to the PVGrid energy simulation software. These functions include the ability to model inter-array shading that occurs as a result of the design ground cover ratio (GCR) and the ability to model the backtracking feature of the PowerTracker. These two features are described below.

Ground Cover Ratio and Module Shading

The ground cover ratio is the ratio of the module height divided by the distance between the module rows. Modeling the impact of GCR is a key aspect of system design. By varying the distance between rows, designers can determine the effect of system energy output. Based on customer system requirements and available space, the optimum GCR is selected.

PowerLight added the ability to enter specific module dimensions, orientation, and the design GCR into PVGrid. The source code was then modified to relate these parameters to the Tracker design and model the inter-array module shading and associated energy loss.

This tool allows PowerLight to quantify the maximum number of modules that will fit within a given area without significantly affecting the energy production of the array. Initial simulations indicate that the optimal GCR for a PowerTracker system installed in California locations is 0.35. At this GCR, the energy loss due to inter-array module shading is less than 2%.

Backtracking Algorithm

In addition to incorporating the GCR and module shading code, PowerLight modified PVGrid to include a backtracking algorithm. This algorithm builds on the GCR and Module Shading modifications described above.

Backtracking maintains a tracking angle that prevents any row from partially shading another so that, while the incident angle is not optimal for each module, all modules will provide some electrical output. Backtracking mitigates inter-array shading when the sun is at low angles. This will increase the total energy capture from the array during periods of the day when the sun angle is low.

PowerTracker systems are programmed to backtrack at the beginning and end of each day when the sun angle is low. If the tracker kept the PV modules aimed directly at the sun during these times, most of the modules would be shaded by the rows next to them. Only the outermost row would have the benefit of full exposure.

At sunrise, the PowerTracker is oriented in the horizontal position. As the sun rises, the modules tracks back toward the sun to prevent interarray shading. Once the sun is high enough – dependent on latitude, array orientation, and row spacing – the modules begin to track the sun’s path across the sky. As sunset approaches, this process is repeated but in reverse, ending with the modules in the horizontal position.

Backtracking is a key design feature that needed to be incorporated into the energy model in order to generate accurate energy predictions specific to the PowerTracker system design. PowerLight developed an algorithm to model the backtracking position for a given GCR and location. The code was then modified to include this algorithm and to model the associated energy output. The new version of PVGrid allows the user to select the backtracking feature in order to quantify the energy difference.

3.2.3 Software Validation

In order to validate the software modifications incorporated into PVGrid, the research team collected data from five operating single-axis tracking PV systems and compared this data to the PVGrid estimate. The location and latitude of each of these systems are provided below in Table 3. These projects were selected based on geographical location and data availability. Only projects with 10 months or more of measured data were selected. The research team also chose a set of projects in diverse geographical locations and latitudes, as shown in Table 3
Table 3, to study the accuracy of shading and sun-angle calculations in a variety of locations.

Table 3. Sites selected for software validation

Project	Location	Latitude
1	Muhlhausen, Germany	49.2
2	Gunching, Germany	49.2
3	Minihof, Germany	48.5
4	Mesa, Arizona	33.3
5	Kona, Hawaii	20.0

Source: PowerLight Corporation

The research team performed a PVGrid simulation with all the relevant design information, including type of module, dimensions, GCR, module electrical characteristics, inverter efficiency, balance of system losses, etc. The authors then compared the expected energy production from each PVGrid simulation to the measured energy production.

3.2.4 Shading Analysis

In order to understand the effect of inter-array shading, the research team used PVGrid to simulate the energy output of a single axis tracking photovoltaic systems in 12 locations, as shown in Table 4.

Table 4. Solar insolation and latitude of evaluated locations

Location	Latitude	Solar Insolation (kWh/m2) Direct Solar Insolation	Diffuse Solar Insolation	Global Solar Insolation
Las Vegas, NV	36.1	1520	535	2054
Honolulu, HI	21.3	1075	890	1966
San Diego, CA	32.7	1081	750	1830
Los Angeles, CA	33.9	1032	767	1797
Sacramento, CA	38.5	1174	621	1795
Beja, Portugal	38.0	1138	627	1761
San Francisco, CA	37.6	1031	689	1718
Lisbon, Portugal	38.4	1014	672	1682
Madrid, Spain	40.3	1023	637	1660
Newark, NJ	40.7	756	699	1453
Munich, Germany	48.2	518	632	1149
Berlin, Germany	52.3	427	572	999

Source: PowerLight Corporation

The research team selected these locations due to the variation in solar insolation and latitude. It is well known that single-axis trackers provide more energy benefit in locations where there is a larger amount of direct and global solar radiation. In addition, these locations also are sited within strong markets for solar energy.

Results of this work are presented in the Project Outcomes section of this report.

3.3 Task 4: Next Generation Structural Design

The primary goal of this task is to analyze the loads placed on the tracker structure from various wind and extreme weather conditions and to use this understanding to optimize the component design. Another goal of this task is to modify system components to install PV at an angle relative to the torque tube, reduce installation labor and capital cost, and eliminates the need for separate grounding conductors for PV mounting. Furthermore, alternative foundations and elevated trackers will be investigated to expand on the types of sites on which trackers can be installed.

The approaches to achieve the goals for Task 4 are discussed below. Results for all activities are described in the Project Outcomes section of this report.

3.3.1 Wind and Structural Analysis

The PowerTracker system design varies depending upon the site conditions. The height of the PV above the ground may be as low as 4′ or as high as 12′ when installed over parking areas to provide shade. Row spacing also varies depending upon the available space and optimization of shading losses as it affects system economics. In addition, sometimes fences are installed around the tracker systems. Some other parameters are variable due to the function of the system and the nature of wind, such as the PV tilt angle and wind angle of attack. PV tilt angle changes throughout the day as the system tracks the sun, and the wind may come from any direction. All of these variables have an impact on wind performance. The wind tunnel test program included a sensitivity evaluation through wind tunnel testing.

The test program, summarized in Table 5, included evaluations of seven system configurations, labeled A-G. Fence types are defined as follows: Type 0 indicates no fence was present; Type 1 indicates a fence was present; Type 2 indicates that a fence was present and an additional diagonal fence was placed at the corners of the array. Exposure relates to surrounding terrain. As defined by the American Society of Civil Engineers (ASCE), Exposure B is applicable to urban, suburban or wooded areas, and Exposure C applies to open terrain with scattered obstructions, having heights generally less than 30 feet including grasslands.

Table 5. Wind Tunnel Test Program for PowerTracker System

Test Configurations for Geometry A

Configuration	Pier Height	Row Spacing	Fence Type	Exposure
A	4 ft	15 ft	0	C
B	4 ft	15 ft	1	C
C	4 ft	15 ft	2	C
D	4 ft	11 ft	1	C
E	4 ft	7 ft	1	C
F	8 ft	15 ft	1	C
G	12 ft	15 ft	0	B

Source: PowerLight Corporation

Other parameters may also vary, such as local wind speeds, surrounding terrain, PV module size and shape, row length, system size, and the shape of the array. The impact on wind loads due to variations in all of these parameters can be evaluated analytically using fundamentals of fluid dynamics combined with wind design standards such as the American Society of Civil Engineers wind design standard (ASCE 7-02). The ASCE-based equations that were used to apply the wind tunnel results are presented in the Project Outcomes (Equations 1-11).

The approach used to evaluate the wind loads on the PowerTracker was to create 1:20 scale models of a basic building block similar to the array shown in Figure 3-3. A photo of the scale model tested in the wind tunnel is shown in Figure 3-4.

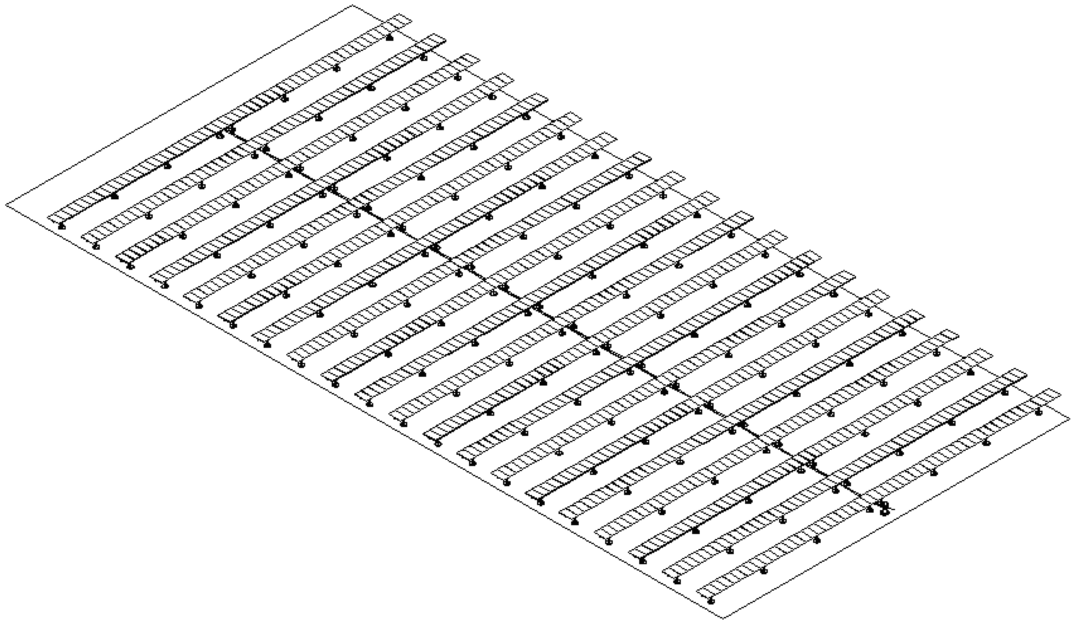

Figure 3-3. PowerTracker System with PV modules mounted flush to the torque tube

Source: PowerLight Corporation

Small-scale models are often used in wind tunnel testing so that large objects such as a tracker system can fit into the wind tunnel, which are typically only 6-8' in diameter. An entire array of PV modules must be studied because the wind loads on individual modules are affected by the PV modules surrounding it. As an example, PV modules located in interior regions of the array are protected from the wind, while PV modules around the edges are more exposed and therefore have higher wind loads.

Figure 3-4. PowerTracker wind tunnel model in the wind tunnel on a rotating platform to vary the angle of the wind as it hit the system. Row spacing, PV height above ground, and PV tilt angle could all be varied on the model.

Photo Credit: PowerLight Corporation

The model (Figure 3-4) was mounted on a rotating platform in the wind tunnel. PowerLight designed the model to vary the following parameters: row inclination angle (-45 [east] to 45 [west] degrees); the distance between rows in the east-west direction; and the height of the system above ground. Pressure taps were placed on numerous PV modules throughout the array and connected to pressure transducers and a data acquisition system so that instantaneous pressures could be measured.

The model was fixed at one PV tilt angle, one row spacing, one height above ground, and with one fence type. The wind tunnel was then turned on at a reference wind speed, and pressure data for all of the sensors was collected at a very high sampling rate for several minutes. After several minutes, the table was rotated so that a new wind angle could be studied. This test was repeated for each wind direction. The PV tilt angles for all rows were changed, and the testing sequence was repeated. Table 6 shows the test program for a system with a pier height of 4′ and fence type 0. The sequence of testing was then repeated for Fence Types 1 and 2, which are defined above. The entire sequence of tests was then repeated for an 8′ pier height and a 12′ pier height. In total, this test program included the evaluation of 81 configurations at 18 wind angles, resulting in 1,458 data sets.

Table 6. Sample test program – 4' pier height, fence type 0

Test No.	Pier Height	Wind Direction	PV Tilt Angle	Fence Type
1	4'	40^o through 220^o at 10^o intervals	-45^o	0
2	4'	40^o through 220^o at 10^o intervals	-30^o	0
3	4'	40^o through 220^o at 10^o intervals	-20^o	0
4	4'	40^o through 220^o at 10^o intervals	-10^o	0
5	4'	40^o through 220^o at 10^o intervals	0^o	0
6	4'	40^o through 220^o at 10^o intervals	10^o	0
7	4'	40^o through 220^o at 10^o intervals	20^o	0
8	4'	40^o through 220^o at 10^o intervals	30^o	0
9	4'	40^o through 220^o at 10^o intervals	45^o	0

Source: PowerLight Corporation

Wind directions and PV tilt angles are depicted in Figure 3-5 and Figure 3-6. Symmetry of the array eliminates the need for testing of wind angles from 221 to 39 degrees. For example, a wind angle of 180^o, which was tested in the wind tunnel, is equivalent to a wind direction of 0^o.

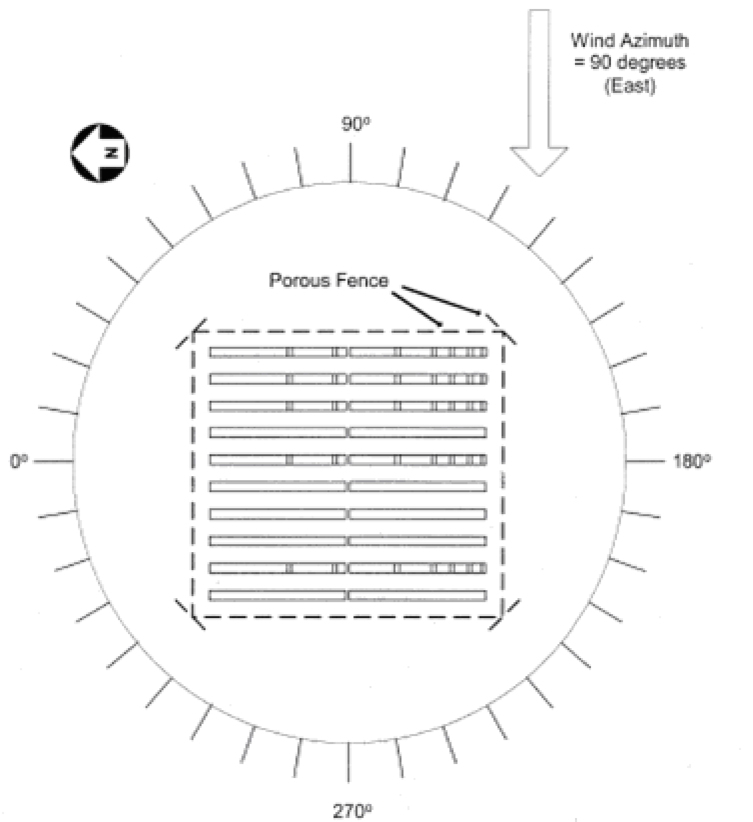

Figure 3-5. Diagram showing model array and wind direction

Source: PowerLight Corporation

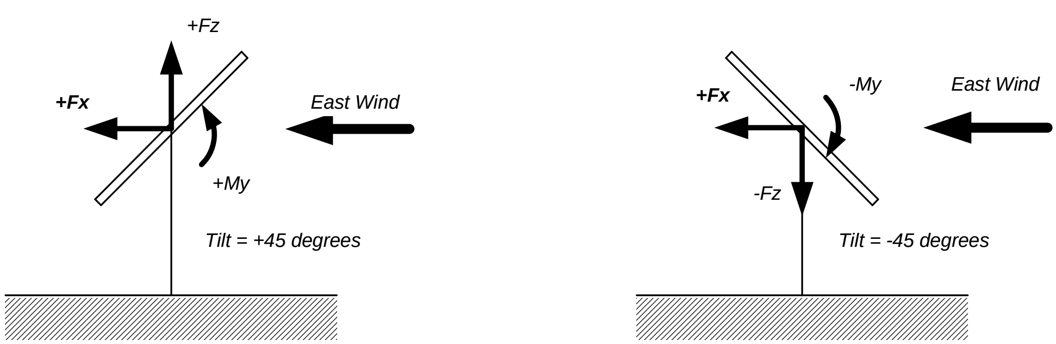

Figure 3-6. Diagram showing PV row tilt angle

Source: PowerLight Corporation

Thousands of pressure measurements were taken on the model in the configurations specified in Table 5 Table 5. The pressure measurements were then analyzed to determine load coefficients on PV modules and structural components such as piers and torque tubes, as described in the Project Outcomes section of this report.

3.3.2 PV Mounting Hardware

Various methods for mounting photovoltaic (PV) modules to the PowerTracker system have been implemented in past years with varying degrees of success. Due to the unique geometry of the PowerTracker system, most of these methods were non-standard based on the specific module manufacturer’s recommended mounting methods. In addition, special precautions had to be taken to ensure that no mechanical interference occurred during operation, as the tracker is a dynamic system. The authors’ approach was to evaluate all the mounting methods used to date, focus on the concepts that worked best, and improve them for future use.

The designs of the PV mounting assembly are governed by the following factors:

1. Cost (Labor and Materials)
2. Aesthetics
3. Compatibility with various PV modules
4. Structural integrity over design life
5. Electrical safety over design life

PV Frames

Because of the diversity of PV frame styles, it is difficult to develop a single method of securing the modules to the 4” structural “torque tubes” used in the PowerTracker system. PowerLight developed two mounting assemblies in order to accommodate conventional PV module frame designs that employ either internal or external flange frames (IFF and EFF, respectively), as shown in Figure 3-7. Standardizing this mounting hardware reduces engineering time required for each installation, regardless of the PV module selected.

Internal Flange frame External Flange frame

Figure 3-7. PV Module Frame Types

Source: PowerLight Corporation

Test Rig

In order to test hardware prototypes, the research team constructed a structural test rig in PowerLight’s engineering shop, as shown in Figure 3-8. The research team built an operational, full-scale section of the PowerTracker system, enabling researchers to simulate field conditions accurately. The research team has used this test rig to model numerous modifications to the tracker system.

Figure 3-8. PowerTracker test rig in PowerLight engineering shop

Photo Credit: PowerLight Corporation

3.3.3 Foundation Design

PowerLight expects to use two foundation types predominantly on its future projects: drilled concrete piers and driven piers. The majority of PowerTracker systems have been built with drilled foundations. Driven piers are a promising opportunity for significant reduction of cost and total embodied energy because they eliminate the use of concrete. Driven piers cannot be used in all soil types, however, so PowerLight expects to maintain an expertise in building PowerTracker systems with both drilled and driven piers. The Project Outcomes section includes a discussion of each foundation type, conditions where one is used over the other, and the design methodology.

3.3.4 High Efficiency Modules

The purpose of this effort was to investigate ways of incorporating high-efficiency modules into the design of the PowerTracker system. In particular, PowerLight was to investigate the inclusion of California-based high-efficiency PV module technologies, such as those provided by SunPower Corporation. An initial investigation identified two promising paths for this effort. One was the incorporation of SunPower modules into the tracker design, and the other was the use of high-efficiency bifacial modules that would benefit not only from their normal high-efficiency output, but also from the reflected light hitting the backside of each module. Both of these paths have been pursued and will soon be deployed in the field.

Crystalline PV cell efficiency has experienced relatively small, incremental increases in efficiency since being introduced to the commercial market in the early 1970s. The basic construction and technology of the crystalline cells have changed little. Recently however, advances in hybrid cells, those that employ both amorphous and crystalline cell technologies, have created the opportunity to increase the overall efficiency of modules. Additionally, cells with all of the contacts on the back surface, e.g. those made by SunPower, Inc., have pushed efficiency levels to 20%. These two technologies were the focus of this effort to incorporate high-efficiency modules into the tracker design.

One hybrid technology not only offers increased cell efficiency, but the ability to gather energy from both sides. Such cells are referred to as "bifacial." Modules constructed with clear encapsulants on both sides can effectively collect light from both sides and capitalize on the bifacial aspects of these hybrid cells. However, conventional PV mounting techniques often preclude the ability of the module to collect light from the "back" side of the module. Typical roof and ground-mounted systems are often designed such that the back of the module is very close to the mounting surface, thus effectively eliminating irradiance to the backside.

PowerTracker tilted and elevated systems being developed as part of this task offer a unique advantage of having measurable energy production from the backside of the modules. PowerLight conducted a series of tests on bifacial modules and existing PowerTracker systems to determine what energy gains this technology may offer to the PowerTracker system. The results of these tests are presented in the Project Outcomes section of this report.

3.4 Task 5: Documentation and Certification

Comprehensive product documentation is critical to ensure product quality and reliability. A primary goal of this effort is to provide complete documentation to ensure proper system installation, facilitate project approval, and demonstrate compliance with applicable codes and certification agencies.

The approach for these activities is described in the following sections.

3.4.1 Design Criteria

The PowerTracker design minimizes structural and foundation costs while ensuring required safety factors. For each installation, a brief customization process is required to design the system to withstand site-specific conditions, such as soil type and wind speed. At the conclusion of this customization process, the pier depth and diameter, row width, and maximum number of rows per drive unit will be determined. These determinations, in conjunction with an array layout, are then used to generate a bill of materials (BOM) for the PowerTracker installation.

Prior to this contract, PowerLight used a labor-intensive method to determine the optimal system design for PowerTracker installations. As part of this effort, PowerLight initiated the development of an automated design process to perform the site customization based on the site parameters. The goal of these activities was to significantly reduce design cycle time and labor requirements. In addition, this automation would result in a standard system design methodology for PowerTracker installations.

In order to achieve these objectives, PowerLight compiled all design rules for the PowerTracker system. PowerLight uses allowable stress design (ASD) for all metal components and follows

Section 1806.8.2 of the 1997 Uniform Building Code (UBC) to design piers to withstand horizontal overturning forces.

From there, a set of design parameters were established as required inputs for the automated design tool. The authors then developed an extensive spreadsheet based on the design rules and inputs from key stakeholders. Extensive testing of the design tool was performed in order to ensure accuracy.

The design tool requirements and use are described in more detail in "Project Outcomes, Task 5."

3.4.2 Documentation Package

Installation Manual

The research team's objective initially was to assemble as much knowledge as possible about the concepts, components, materials, and constraints inherent in the implementation of a PowerTracker Solar Power System.

Initial research included sending the individuals involved with PowerLight documentation on several trips to PowerTracker installation sites to observe both completed projects as well as systems that were in various stages of progress. Careful analysis of each phase of the construction was undertaken with the latter, and the objective was always to uncover not only the nuances of integration among each step of each phase of construction, but the practical logistics involved in their execution.

Discussions with construction managers, site supervisors, project managers, and subcontractors all yielded valuable perspective and insight into how to best describe the procedures necessary to install a PowerTracker Solar Power System.

During the drafting of the installation manual, construction managers continued to circulate ideas and methods, as well as share their lessons and triumphs as they oversaw PowerTracker installations around the United States. This open forum yielded consensus on several of the more complex procedures, in addition to expediting the installations overall.

Installation teams were able to realize substantial time savings, especially during the following specific steps:

- Pre-construction Material Placement: This logic behind this positioning of system components enables workers to minimize down time between steps.
- Pedestal Hole Creation Techniques: Different hole-creation techniques have shown to be better suited to particular soil conditions and compositions. The authors describe three methods in the Installation Manual, so that the construction manager can employ the best approach for the specific conditions at a given site.
- Alignment Strut Welding Sequence: Critical because these struts ensure the perpendicularity of the drive pedestal and the adjacent bearing pedestals, and therefore

the alignment of the drive unit; several methods have been used by installation teams, and the authors now describe the most effective method in the Installation Manual.

- Bearing Pedestal Cap Alignment: Because the caps must be in the same plane, this can be a challenging step, especially when rows are particularly long. Different approaches have yielded mixed results, and construction managers have been able to share the advantages of each.
- Torque Tube Alignment and Welding: This is perhaps the most temperamental step of the PowerTracker installations; several methods have shown consistent, successful results. The authors describe the most commonly applied method.

Drafts of the installation manual were then taken into the field by installation teams and used to instruct their implementation of each phase of an installation. Subsequent and regular "post-mortem" meetings were held wherein individuals could share the experiences they had with each phase of system construction and debate the merits of each approach. Key stages of the construction process were captured with digital photography in order to enhance the usability and clarity of the document.

Operation and Maintenance Manual

The research team's objective was to thoroughly analyze each of the sections in the existing PowerTracker Operation & Maintenance (O&M) manual, to identify ways in which the authors could more effectively target the specific types of information it contained, and better present that information to the relevant audiences.

The authors wanted to revisit all of the information in the manual, as well as reevaluate the effectiveness and format of the documentation, both in its context and as it related to its target audience. The goal was to make the information as up to date as possible and to regroup it so that its usability was optimized according to its likely audience.

After breaking out the sections in the existing manual, each was sent to all individuals within the company who had at least some degree of subject matter expertise, or who had some occasion to refer to the manual. This resulted in the sections being sent to a large number of people. After reading their respective sections and updating the text to reflect the evolution of best practices and feedback-informed procedural changes, these individuals held meetings to discuss the best ways to update and otherwise modify the sections to best serve their intended audiences.

3.4.3 Certifications

PowerLight strives to achieve agency approvals for all of its products. Not only do these certifications help ensure that the company's products function in a safe manner, but they also help greatly to simplify permitting at the local project level. For the controller, European certification (CE) testing was pursued for both safety and electromagnetic compatibility. This certification improves PowerLight's ability to disseminate the PowerTracker technology worldwide.

3.5 Task 6: Next-Generation Electrical Design

The goal of this task was to evaluate the current methods of addressing the DC electrical design of the PowerTracker system. Specific elements of the DC wiring that are often customized on a project-by-project basis are obvious candidates for standardization. These elements include module-to-module wire routing, homerun wiring practices, system grounding, routing wires between moving and stationary components, and DC combiner boxes.

The approach to develop the next-generation electrical design is discussed below. Results of this effort are presented in the Project Outcomes section of this report.

3.5.1 Module-to-Module String Connector Routing and Securement

For ground-mounted systems, the module-to-module wire routing has often been improvised in the field. While still providing a safe and reliable system, this has required extra engineering time for each installation and contributed to a "messy" look and lacked consistency from job to job. The research team decided to standardize this element to minimize engineering costs and to ensure that proper safety precautions were dealt with consistently and that the final systems would have a clean and consistent visual appearance.

Part of this effort meshed with the authors ongoing work with PV suppliers to address the authors specific needs. In this case, the length of the module lead wires was specified at an optimal length for connecting modules along the tracker torque tube. An objective of this effort is to optimize this length to limit the amount of additional securement used and to minimize voltage drop throughout the system. Due to the large size of many PowerTracker systems, a small increase in module lead length can add up to a measurable drop in system performance. The research team also specified the use of coated metal wire ties for some types of systems. These wire ties have a higher outdoor design life than plastic ones and are appropriate for systems exposed to extreme weather conditions.

For elevated systems, customers often request that the wires be hidden as much as possible. This request is driven equally by aesthetic and safety concerns. Exposed wiring can be unsafe in some situations where wiring is publicly accessible, and it also lacks a professional appearance. The research team set out to design wire trays that would hide the module lead wires and offer a safe, tamper-resistant method of routing these wires.

3.5.2 Homerun Wire Routing and Securement

Trackers have a unique requirement to route the DC wires from moving components (PV modules mounted on the torque tube) to stationary structural components (support pedestals and DC combiner boxes). The systems have long design lives of 20 years or more, which means that the wire and conduit must be able to survive 20,000 or more cycles while being subjected to temperature cycling and exposure to ultraviolet radiation. Many off-the-shelf conduits are available with specifications that claim to meet this requirement. However, PowerLight's experience has been that most of these claims do not hold up. In order to find a material that would hold up under these conditions, the research team designed a test fixture that could speed up the motion of this transitional joint so that 10 years of cycling could be accomplished within a 24-hour period. The research team performed the equivalent of 150 years of cycling with no observed signs of failure.

Along with a solution for the transition of the homerun wiring from the moving frame to the fixed frame, a standard method was needed for routing these conductors from one row to the next. In the past, this routing was accomplished in a few different ways and often improvised in the field. This lack of design direction led to delays in project completion and was subject to subcontractor preference. The research team set out to engineer a standard wiring method that provided the aesthetics and safety elements desired while also providing the required cost savings. By implementing an off-the-shelf covered wire tray, the authors were able to reduce lead times and additional manufacturing cost, while gaining a safe and aesthetically pleasing solution applicable to both elevated and ground mounted trackers. These wire trays also (i) provided for a rapid wiring installation; (ii) reduced the number of electrical boxes by more than half; and (iii) eliminated trenching within the array, a method previously common for ground-mounted installations. As an alternative solution, ultimately used for cost comparison, the research team designed a wire tray that offered similar wire routing benefits for ground mounted systems.

3.5.3 System Grounding

In order to ensure the authors' systems are properly grounded and meet all applicable safety codes, the research team set out to establish two baseline methods for bonding the modules together and to the corresponding torque tube. The two methods are for the two standard frame types, as shown in Figure 3-7, for which mounting hardware was developed under Task 4. The methods were carefully researched to ensure that they would be installed the same way every time and that they complied with all applicable safety codes.

As with the home-run wires, one of the biggest challenges was finding a grounding method that could connect the moving frame of the tracker to the fixed frame of the support structure. Various types of grounding wires and connectors were installed on the test fixture. These components were subjected to accelerated-cyclic testing to determine which would be capable of surviving well beyond the expected life of the PV system.

For system level grounding, the research team worked to develop guidelines for efficient supplementary electrode grounding paths, taking into account the location of adjoining tracker array blocks, level of lightning activity at the site, DC cable trench requirements, and added redundancy. These guidelines would help define the methods for integrating these supplementary ground electrodes with major electrical equipment, equipment pad ground rings, and ground rods.

3.5.4 DC Combiner Boxes

Using large combiner boxes at central locations is common in large-scale commercial PV systems. In rooftop systems, this is especially true where an equipment room usually offers a convenient place to terminate all the DC wires from the roof. In tracker systems, large centralized boxes lead to large bundles of exposed wire or excessively sized conduits. These can be unsightly, and it becomes a difficult design challenge to incorporate these into the moving parts of a tracker.

For these reasons, commercially available 12-string boxes have previously been used, placing one box at every row or every other row. Although successful from a reliability standpoint, this method was too costly due to the number of boxes that must be installed in a typical tracker system. During one of the authors' earliest ground mounted tracker installations, the research team used a combination of pull boxes and 10-string combiner boxes as required. From this installation, the authors experienced extensive material and labor cost due to the sheer number of electrical boxes installed and the excessive length of trenching required facilitating these combiner boxes to the electrical equipment pad.

A careful cost and sizing analysis was conducted to determine the optimal box size to balance field labor with typical tracker sizing and physical size constraint issues. Work was carried out to design a custom box based on the results of this analysis. While there are other high output combiner boxes commercially available, none accommodates the required higher number of strings. In addition, the hardware costs for the custom combiner boxes were a key design parameter. The results of this design effort and resulting cost savings are presented in the Project Outcomes section of this report.

3.5.5 Commercial Demonstration of Results

As with most design improvements, it is not enough to create the designs themselves. In order to be completely successful, the designs must be implemented in the field. This allows the engineers to get insight into the efficacy of the new designs and feedback from field personnel on the ease of installation of the new hardware. It also provides verification of the anticipated improvements in cost or performance. In order to gauge the success of the improvements developed under this task, PowerLight installed a 251 kilowatt-peak (kWp) elevated tracker system in Fremont, California, that incorporated all of these improvements applicable to the elevated tracker. This demonstration system is discussed in further detail in Section 4.6.5.

4.0 Project Outcomes

4.1 Project Objectives

Table 7. Summary of objectives and outcomes

Objective	Goal	Actual
Reduce PowerTracker life cycle costs	36%	19%, excluding PV + 10% Add'l Savings Expected from O&M Savings
Reduce cycle time from system design to installation	40%	58%
Improve reliability and durability to reduce unscheduled maintenance	65%	Long-term data needed
Reduce steel waste stream	70%	20%

Source: PowerLight Corporation

4.1.1 Life Cycle Costs

Under this project, PowerLight set a goal to reduce PowerTracker life cycle costs by 36%. During the 32-month duration of this project, PowerLight measured a 19% reduction in non-PV life cycle costs.

Table 8. Improvements to life cycle cost and cycle time

Site (NJ)	System Size (kWp)	Normalized life cycle costs	Cycle Time (days/kWp)	Direct Labor ($)	Materials	Subcontractors
Baseline	500	100%	3.25	100%	100%	100%
Current	505	81%	1.35	45%	76%	91%
Reduction		**19%**	**58%**	**55%**	**24%**	**9%**

Source: PowerLight Corporation

This reduction in life cycle costs was achieved through significant labor savings due to improvements in design processes (Task 3 and 5) and installation procedures through implementation of designing for ease of installation (Tasks 2, 4, and 6) and improved documentation (Task 5). These developments also led to efficiency improvements of construction subcontractors. In addition, design efforts under Tasks 2, 4, and 6 focused on raw material cost reduction, which had the largest impact on decreasing total project cost.

PowerLight made additional improvements to the PowerTracker components to improve long-term reliability. These enhancements are projected to realize at least 10% additional life cycle savings through reduced operation and maintenance (O&M) costs. While the measurable projected savings due to project activities appears to fall short of the target, PowerLight is confident that many of the design principles employed will have further cost reduction impacts in the future.

Due to an industry-wide PV shortage, PV costs have increased significantly. When taking into account total life cycle costs (including PV), PowerLight measured an 11% reduction. To evaluate progress toward this objective, PV costs were subtracted from the total life cycle costs in order to remove the impact of PV market conditions.

4.1.2 Cycle Time

With the goal of reducing project cycle time by 40%, PowerLight worked to streamline design, procurement, and installation procedures. By further standardizing the PowerTracker system design (Tasks 2, 4, and 6), PowerLight realized significant decreases in upfront design costs. By documenting the design process with the creation of the TrackerCalc design tool under Task 5, the cycle time was further decreased. Because TrackerCalc also automatically creates a bill of materials, the procurement process was simplified, requiring less labor and time. In aggregate, these improvements resulted in an approximate reduction in cycle time of 58% (Table 8).

4.1.3 Reliability and Durability Improvements

The long-term objective of reducing unscheduled maintenance by 65% through reliability and durability improvements will be proven over the lifetime of the improved PowerTracker systems. The most significant improvements will be derived through the implementation of the new controller developed under Task 2. Since fielding the new controller, PowerLight has not logged a single failure. In a similar time frame, the previous generation experienced numerous failures. However, due to the short duration in which the new controllers have been operating and the relatively low quantity of new controllers fielded, no data of statistical significance can be reported at this time.

4.1.4 Steel Waste Stream

From the outset of this project, PowerLight worked to reduce the steel waste stream by 70%. For concrete pier foundations, a waste stream of approximately 12.5% is generated due to cutting and leveling piers, and this waste is then recycled. Under Task 4, PowerLight developed driven-pier foundations, which results in no steel waste as the pier is driven to the exact depth required. In 2006, PowerLight installed approximately 6,500 piers, of which 1,280 were installed using the driven pier method. As a result, PowerLight reduced the steel waste stream by approximately 20%. As the number of projects with driven pier foundations increases, the authors anticipate this waste stream reduction will approach the 70% target.

4.2 Task 2: Controller and Drive Improvements

PowerLight believes that its approach to improving its drive unit and controller as described in the previous section resulted in a successful project that generated a design far superior to earlier efforts. The following sections detail individual aspects of the design and how they contribute to the overall success of the project.

4.2.1 Controller Design

The final controller design was accomplished exclusively with off-the-shelf industrial components. Figure 4-1 shows the final controller design identifying the key components. Of the identified components, note that all are available off-the-shelf, including the programmable logic controller (PLC), variable frequency drive (VFD), and GPS unit. The use of off-the-shelf components allows PowerLight to leverage the cost structure, reliability, and performance of existing technology while reducing design time and resource usage. A custom solution is also not likely to generate enough volume to generate economies of scale needed to reduce cost significantly.

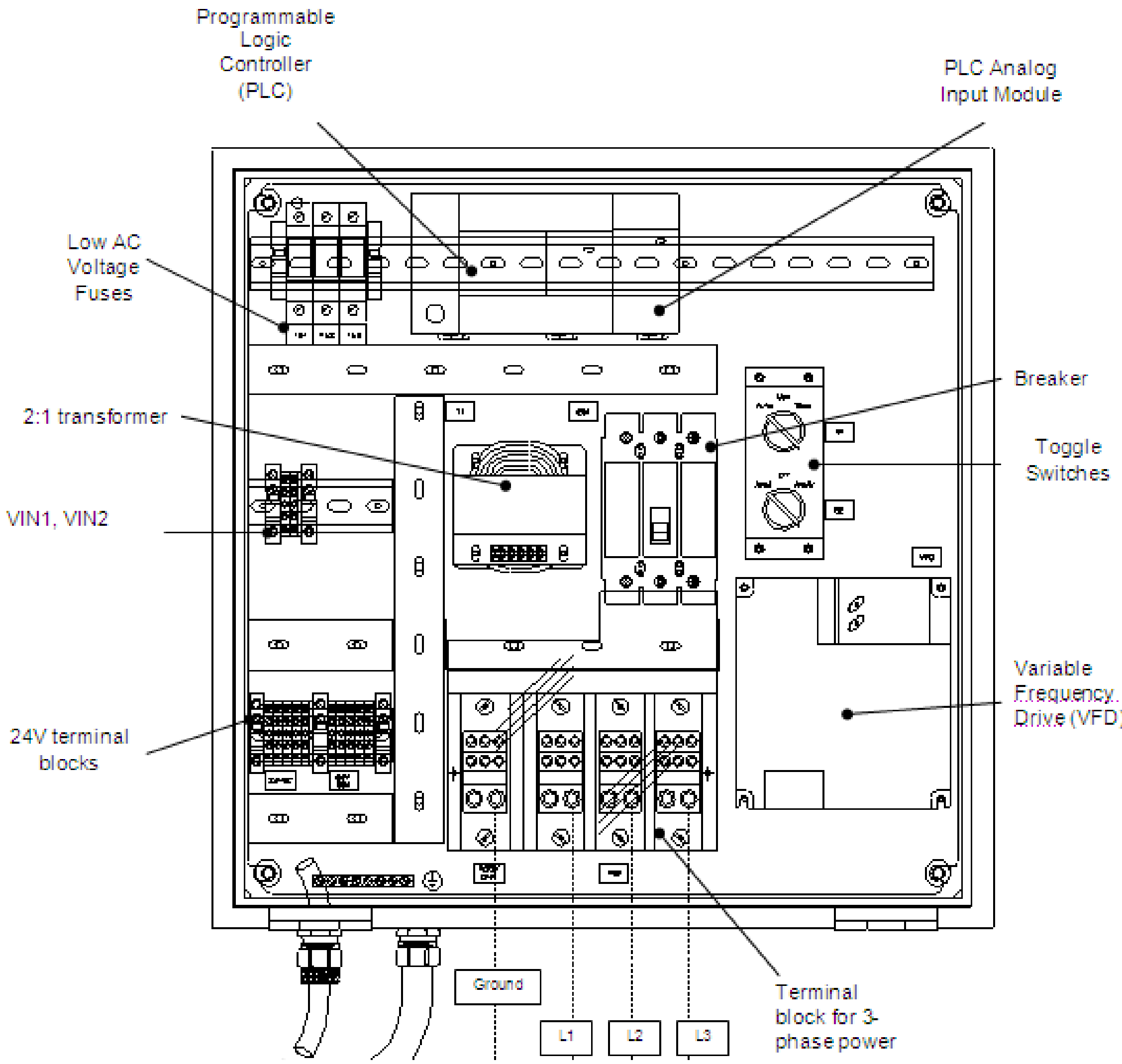

Figure 4-1. Controller Layout.

Source: PowerLight Corporation

Tilt Angle Feedback / Inclinometer

Prior control systems measured tilt angle using a potentiometer. The resolution of this sensing is no more than 8 bits, resulting in a resolution of about 0.35 degrees. Despite the relatively low resolution available with the potentiometer, the system tracking accuracy was deemed sufficient. However, the potentiometer had many other drawbacks, not the least of which was lack of long-term reliability. As a result, the potentiometer was replaced with an inclinometer, the benefits of which are described in the following sections.

Torque Tube Actuation

For more reliable and precise motor control, a variable frequency drive (VFD) was included as part of the control system. With the VFD in the system, there are many possibilities for motor control. The authors are currently running the VFD only at a single frequency, 60 Hz, during normal operation. A simple bang-bang control with a deadband of +/-(0.35/2) degrees (+/- 0.17 degrees) is used to determine when the motor should run, with the goal of keeping the duty cycle low for long-term reliability purposes. With roughly 0.09 degree measurement resolution from the inclinometer, this results in 2 bits of resolution inside the +/- 0.17 degree deadband.

Running at the automatic operation speed, the feedback signal from the inclinometer should change every 5 to 6 seconds. This suggests that the control loop needs to run on no more than a 5-second interval.

4.2.2 GPS System

Global positioning system hardware is becoming ubiquitous in a wide range of applications from cell phones to car navigation systems. As such, commercial components have become relatively inexpensive. A commercial GPS unit targeted at marine applications was chosen for integration into the controller. The unit connects to the PLC via a standard serial link and supports a proprietary command set.

This GPS unit performs two functions:

- Accurate source of time and date
- Determination of system location

Timekeeping

Although not a well understood problem, it is actually relatively difficult to build a clock that can track time extremely accurately over very long time periods (i.e. years). While small time errors would generally only result in very small tracking errors, PowerLight’s controller requires a much more accurate measure of time. The primary reason for this is the company’s backtracking technology, which prevents shadowing between panes at low sun angles. The backtracking algorithms are very sensitive to the exact time and date, and thus clock drift of only a few minutes will result in less than optimal energy output.

Since the real time clock present in the controller is reasonably accurate over short periods (days and weeks), it is only necessary to calibrate it infrequently. As such, the GPS clock signal is used to periodically update the controller’s internal time and thus eliminate the effects of long-term errors.

System Location

Typically, part of commissioning a solar tracking system requires setting up the system specific controller parameters. Among these parameters is the system location, which is defined by its longitude and latitude. Without accurate location information, the controller will not be able to accurately determine the exact location of the sun at a given time.

With the GPS system installed, determination of the system location becomes trivial to the technician performing the configuration. The GPS unit communicates the exact location directly to the controller, which then displays the result to the operator for verification. As this is the primary function provided by GPS, there is very little reason to expect any errors from this operation. Overall, the GPS functionality reduces the chance of configuration errors and shortens the configuration time.

4.2.3 Improved feedback system

Due to prior performance and reliability problems with the potentiometer used for tilt angle feedback, a new measurement technique was desired. As a higher reliability alternative, the controller developed as part of this project uses a solid-state inclinometer. Compared to the potentiometer feedback mechanism, this approach has three major advantages:

- Inherently higher reliability
- Higher resolution (0.09 degrees versus 0.35 degrees)
- Direct measurement of angle in two axes.

Of these, the primary driver for cost reduction comes from the combination of higher sensor reliability and direct angle measurement. As would be expected, feedback failures in a closed loop control system can have catastrophic consequences. In particular, if the feedback device fails, the controller will attempt to move to a position that it never seems to reach. This typically results in the system running to the end of travel in one direction. To prevent system damage, limit switches or some other hard stops must be incorporated into the system at substantial additional cost. A service call will also be necessary after a feedback failure to replace the sensor or fix the problem. Use of an inclinometer is expected to provide higher reliability over time and thus reduce the costs associate with feedback errors.

The inclinometer input is measured with an analog input module with a 0-10V range. In automatic operation, the mechanism runs at roughly 1 degree per minute, with the sensor frequency in the 0.1-0.2 Hz range. A simple boxcar filter is applied to the raw sensor reading. A boxcar was chosen because:

- 32 bit floating point math (not 64 bit) on the PLC will for all intents and purposes prevent the use of recursive filters.
- Storing coefficients for more efficient non-recursive filters is unwieldy on the PLC, and since compute efficiency is not of significant importance, a simple boxcar is an obvious

choice. Figure 4-2 shows a plot of the filter performance.

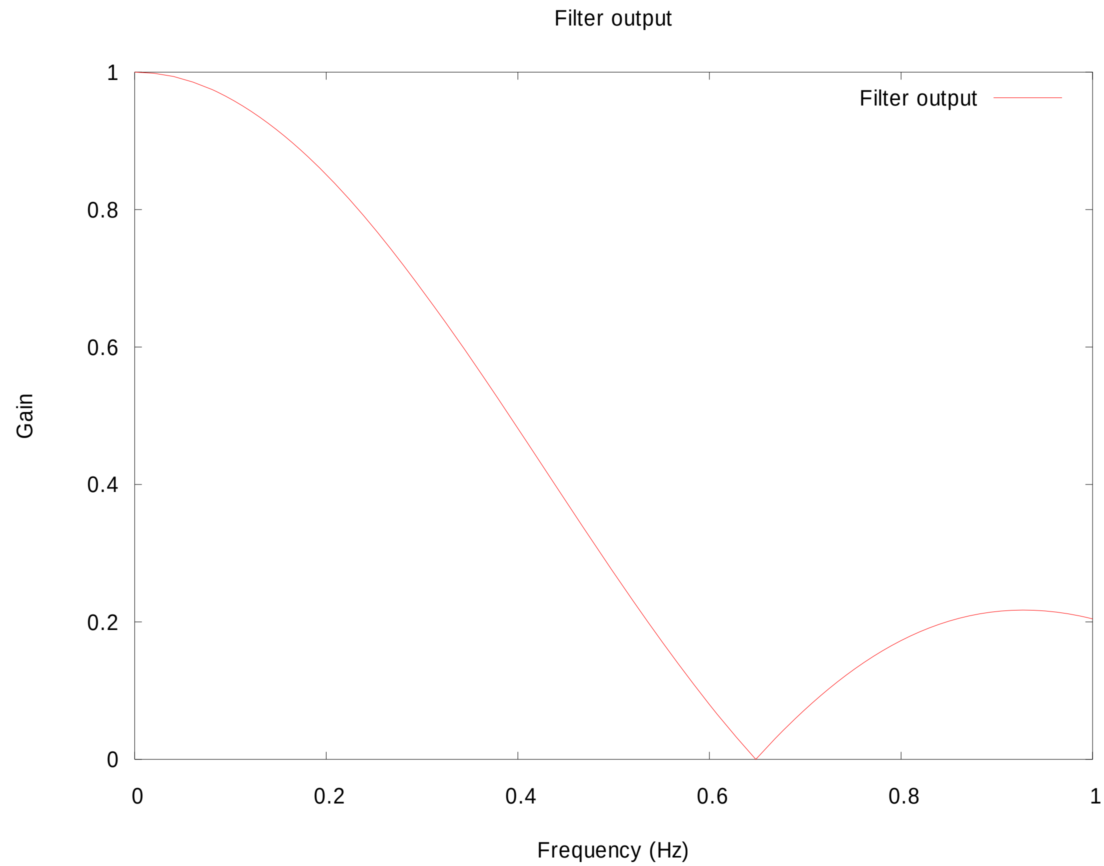

Figure 4-2. Tilt angle measurement filter.

Source: PowerLight Corporation

4.2.4 Networking

PowerLight originally proposed that the controller also include a network interface that would allow remote access to the system in the case where a network connection was available. After a detailed cost/benefit analysis, PowerLight determined that the cost of including a network interface on each controller was too high given the functionality it provided. The required components for such an interface included a network interface card, fiber optic transceiver, and cabling that would increase the cost of the controller by at least 30%. In return, each controller would be available on-line for remote diagnostics, with implementation of this feature. Given that the system was also being designed for high-reliability, stand alone operation, the added cost was deemed unjustified.

4.2.5 Upgraded Configuration Software Interface

As part of the effort to improve the system commissioning process, an improved controller user interface was also developed. The software runs on a PC that is directly connected to the controller. The software includes multiple screens that display current system information and allow for changes to be made to configuration variables. The following are examples of the screens available and descriptions of the variables contained on each.

PowerTracker User Interface

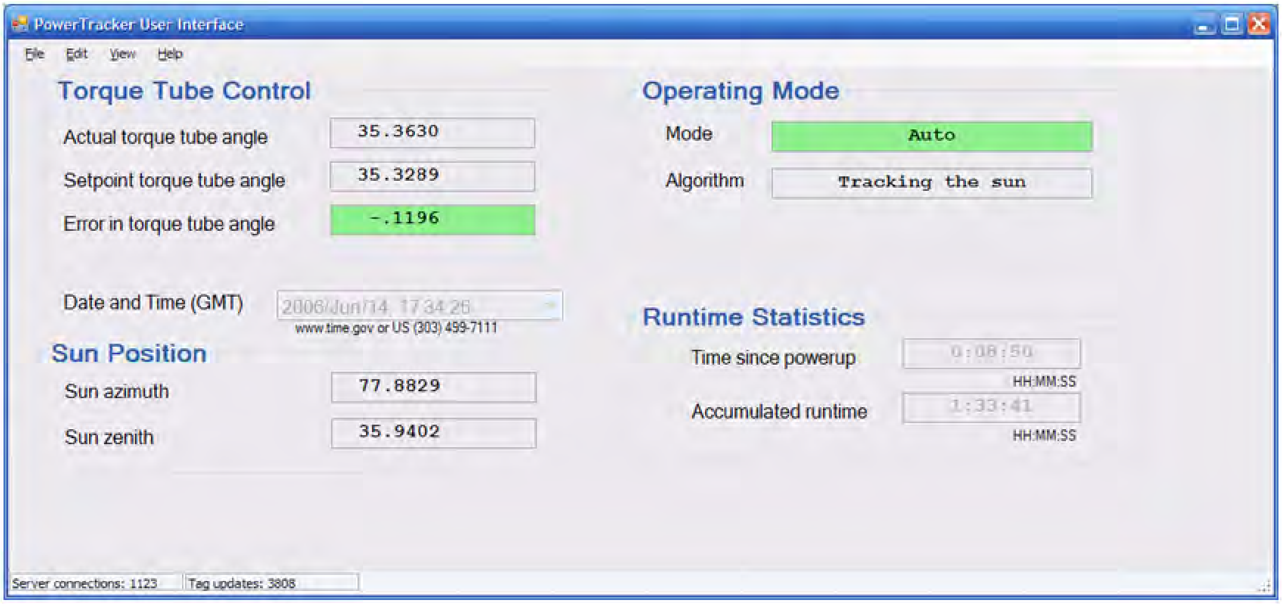

Figure 4-3. User interface screen

Source: PowerLight Corporation

Table 9. User interface fields

Field	Definition
Actual torque tube angle	The current angle of the torque tubes.
Setpoint torque tube angle	The position to which the controller is attempting to move the torque tubes.
Error in torque tube angle	Torque tube angle error: the difference between the actual and setpoint torque tube angle.
Date and time (GMT)	The date and time from the controller (always Greenwich Mean Time [GMT]; *do not* enter local time). You enter this time and date on the Edit Date and Time screen; it cannot be modified from this screen.
Sun azimuth	Calculated sun azimuth; this value is calculated based on time of day, date of year, and site parameters.
Sun zenith	Calculated sun zenith; this value is calculated based on time of day, date of year, and site parameters.
Mode	Current operational mode (*Automatic, Manual,* or *Stow*).
Algorithm	Translation of the current Mode.
Time since powerup	The time elapsed since been since the controller was last powered up.
Accumulated runtime	The total time elapsed since the controller has been running (since its installation).

Source: PowerLight Corporation

Edit Site Parameters Screen

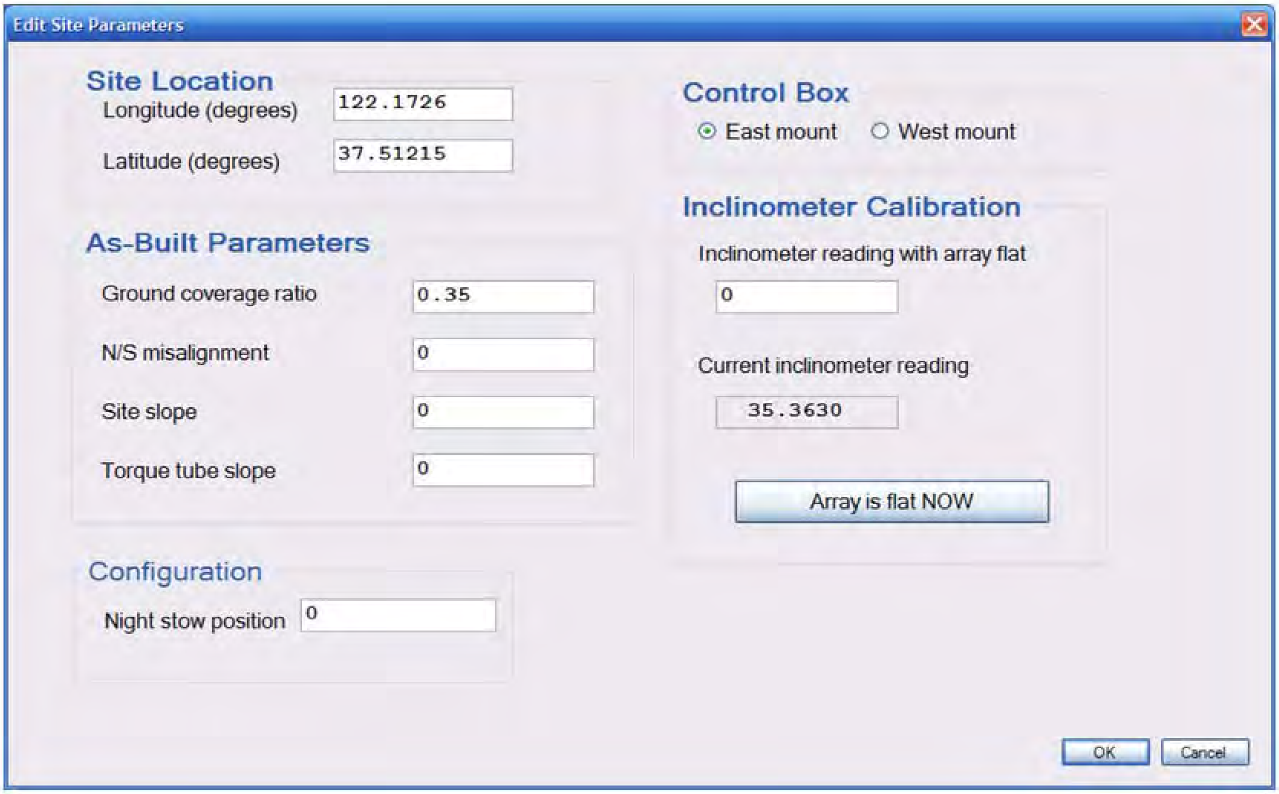

Figure 4-4. System setup screen

Source: PowerLight Corporation

Table 10. Setup screen parameter descriptions

Field	Definition
Longitude (degrees)	Longitude coordinate for the controller's location. Note. This value is measured as the number of degrees west of the prime meridian.
Latitude (degrees)	Latitude coordinate for the controller's location. Note. This will be negative if the controller is in the Southern Hemisphere and positive if it's in the Northern Hemisphere.
Ground coverage ratio (GCR)	The percentage of total ground surface taken up by the system when viewed from above with the modules flat. A smaller GCR means that modules are proportionally farther apart. GCR should typically be in the range of 0.35 for a ground-mounted system, and 0.50 for an elevated system.
N/S misalignment	The number of degrees by which the torque tube alignment is off from true N–S. If the value is positive, the tube alignment is clockwise from true N–S when assessed from overhead.
Site slope	The E–W slope of the site on which the system is installed. The value is positive when the drive strut slopes downward toward the east.
Torque tube slope	The slope of the torque tubes once they are installed. The value is positive when the south end of the array is lower than the north.
Night stow position	A programmable position. This represents the number of degrees at which the modules are positioned and at which they remain overnight.

Field	Definition
Control Box	Select East mount or West mount depending on which side of the array the screwjack and controller are mounted (the controller must always mount on the north side of the screwjack).
Inclinometer reading with array flat	The torque tube flat offset, in degrees, read from the inclinometer. This value is positive when the array, positioned flat by the operator, is tilted toward the east.
Current inclinometer reading	A real-time display of the torque tube tilt. This value is helpful when determining the torque tube flat offset.
Array is flat NOW	Click this button after you have positioned the array flat.
OK	When all site parameters on the screen are correct, click this button to store them in the controller.
Cancel	Click this button to exit the screen without making any changes to the controller.

Source: PowerLight Corporation

4.2.6 Installation tooling

Two sets of installation tooling were developed to improve the accuracy of drive unit placement in the field.

Drive Pier Cut-off Fixture

The cut-off fixture establishes the proper height and array plane for drive unit, eliminating what was previously an "eyeballing" of the cut by the metalworker (Figure 4-5). Better control over the pier height should help to reduce the chance of mechanical binding due to misalignment error.

Figure 4-5: Cut-off fixture for drive pier
Photo Credit: PowerLight Corporation

Figure 4-6: Alignment struts for drive pier
Photo Credit: PowerLight Corporation

Drive Pier Alignment Struts

Drive alignment struts were also designed into the system to help with alignment between the drive pier and the first row of PV (Figure 4-6). The struts properly position the drive pier relative to the first torque tube and provide reinforcement of the drive pier by distributing load to adjacent piers. Much like the cut-off fixture, the alignment struts reduce the chance of mechanical binding due to misalignment error. The struts also significantly reduce field calibration time as the assembled system is installed with known offsets.

4.2.7 Prototyping

Prototypes of the drive unit and controller were constructed for validation and testing purposes. Prototype units were tested in PowerLight's R&D lab in conjunction with testing on structural elements designed under Task 4. Figure 4-7 shows the preliminary prototype of the next-generation controller.

The prototype controller includes the following features

- Industrial standard PLC controller
- Variable frequency drive
- Solid state inclinometer to measure PV rotational angle
- Requires no limit switches or additional feedback
- All components UL/CE certified
- Ethernet connectivity (Optional)
- Real time clock with max 45 s of annual drift
- 208 VAC 3-phase, 400 VAC 3-phase
- Windows-based development interface

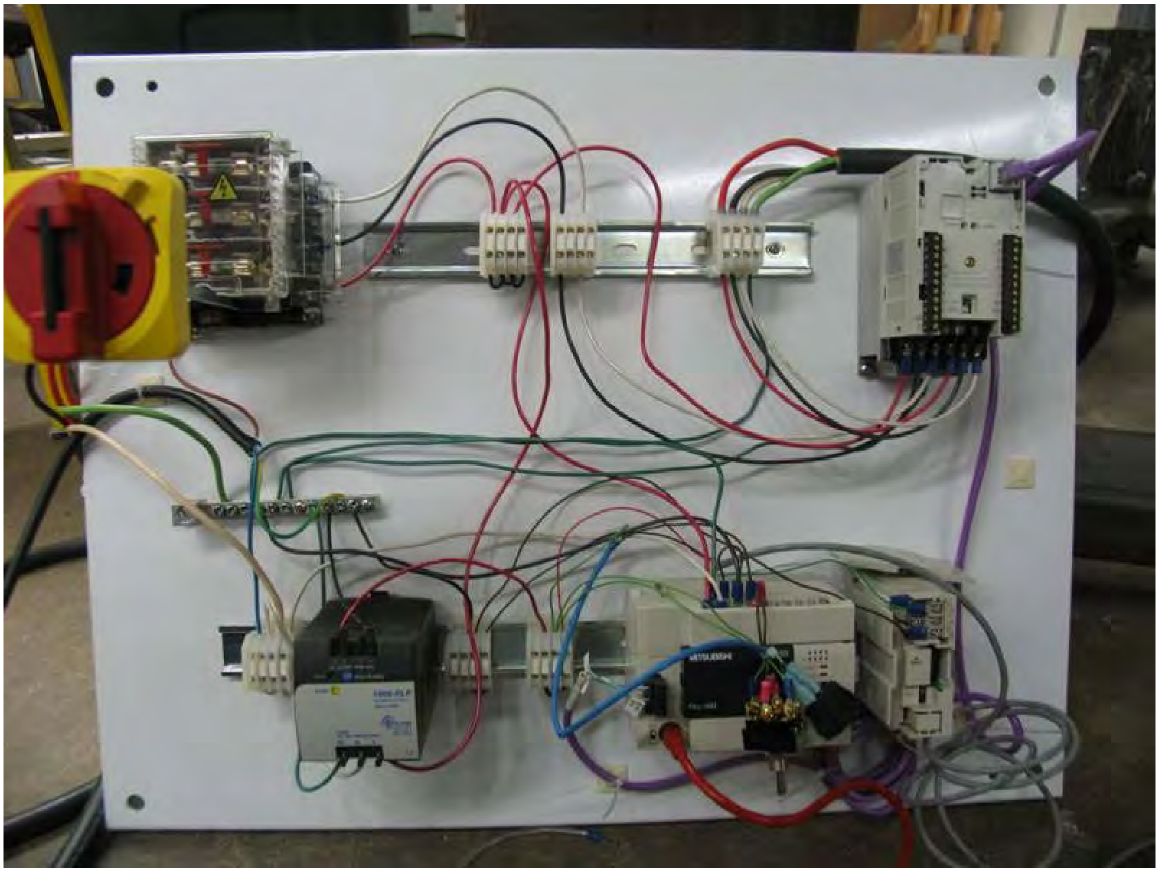

Figure 4-7: Controller prototype system used for preliminary development work
Photo Credit: PowerLight Corporation

4.2.8 Commercial Demonstration

Within the United States, PowerLight has installed final versions of the controller at three working commercial projects in California during 2006, all of which have been operational since May. These controllers have been operating without any reported issues since installation. Further, field reports suggest that installation and upgrade of the controllers went smoothly.

The following table lists the existing installations of the new controller along with basic project information.

Table 11. Commercial demonstration systems

Project Name	Location	Date of Installation	System Size (kWp)	No. of Controllers
Alameda Public Works	Hayward, CA	April 2006	252	2
USPS San Francisco	San Francisco, CA	May 2006	205	1
Napa Valley College	Napa, CA	May 2006	1,157	5

Source: PowerLight Corporation

Operating performance of these systems has been monitored closely. Figure 4-8 shows sample tracking accuracy data for the improved controller and drive. In the figure, tracking data over a 24 hour period shows multiple tracking phases, including night time stowing, backtracking, and tracking. Note that during the sample period, tracking error was well within an acceptable range of ±0.2 degrees.

Figure 4-9 shows energy collection performance for the Napa commercial system over a seven-day period. While December is not particularly sunny, note that energy output tracks the irradiance data closely throughout each day.

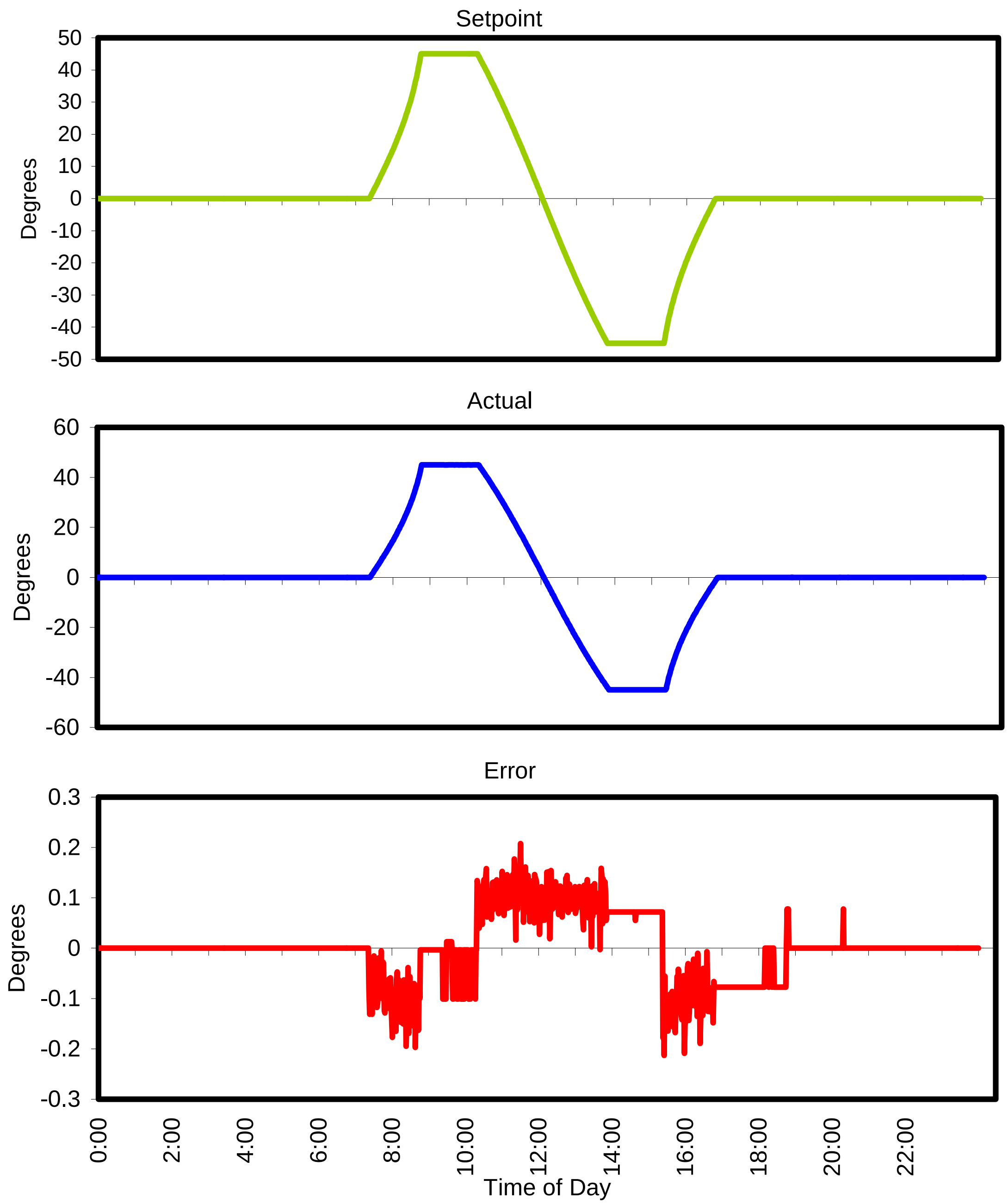

Figure 4-8. Sample data for position tracking performance of controller installed at demonstration site

Source: PowerLight Corporation

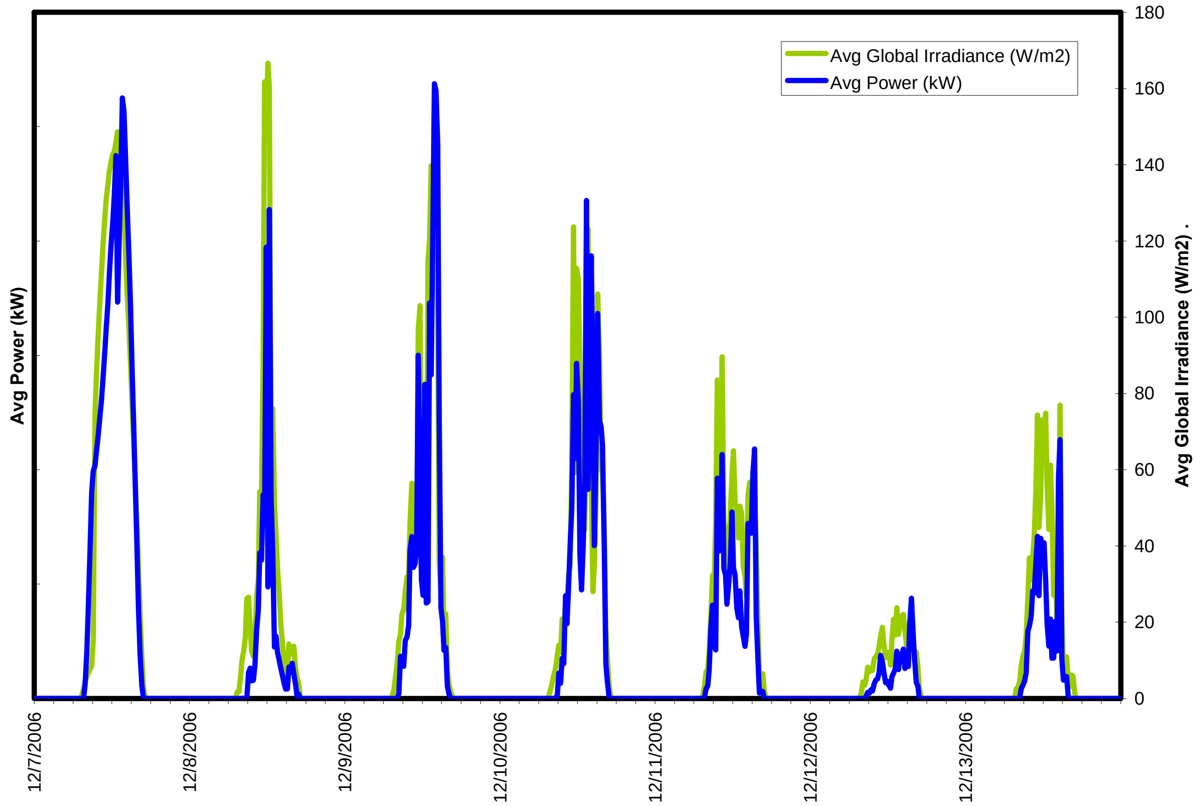

Figure 4-9. Energy production and irradiance at commercial demonstration site over a seven-day period from December 7-13, 2006

Source: PowerLight Corporation

4.3 Task 3: Design Tool Improvements

4.3.1 Software Selection

PowerLight chose to modify PVGrid, an existing software program, based on the results of a preliminary survey of existing software. PVGrid is based on a software package called PVForm, which was developed by Sandia National Laboratories and has been in use since 1988. Energy predictions have been validated against hundreds of operating PV systems.

PVGrid provided the authors with a base source code that could be modified over time to incorporate more parameters specific to PowerTracker technology. The research team modified the software to include ground cover ratio (GCR) analysis, module shading, and backtracking, as described below. This software will help to accurately predict and compare energy production for both PowerTracker and fixed PV systems.

4.3.2 Software Modifications

PowerLight modified the existing PVGrid software to incorporate the functions required for the PowerTracker configuration. The original PVGrid software was a DOS application, which has become difficult to maintain with modern computer operating systems. The modifications to the code were made to the DOS version at first to ensure that they functioned properly. The final version of the software runs as a Windows application (visual basic and C++). Figure 4-10 and Figure 4-11 show sample screens of the new features included in the original DOS software as well as the new Windows based interface.

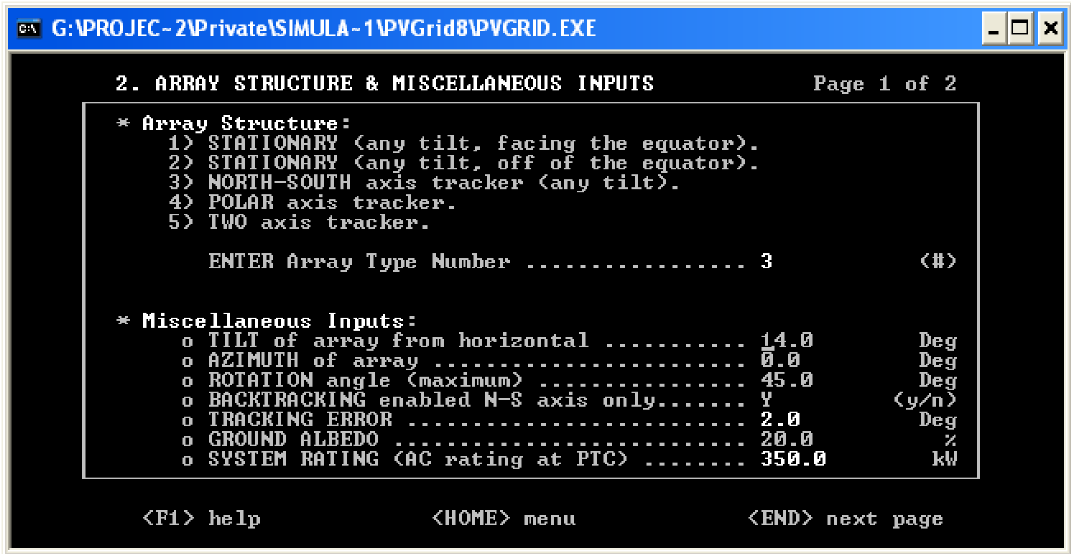

Figure 4-10. Screenshot of new features in original DOS software

Source: PowerLight Corporation

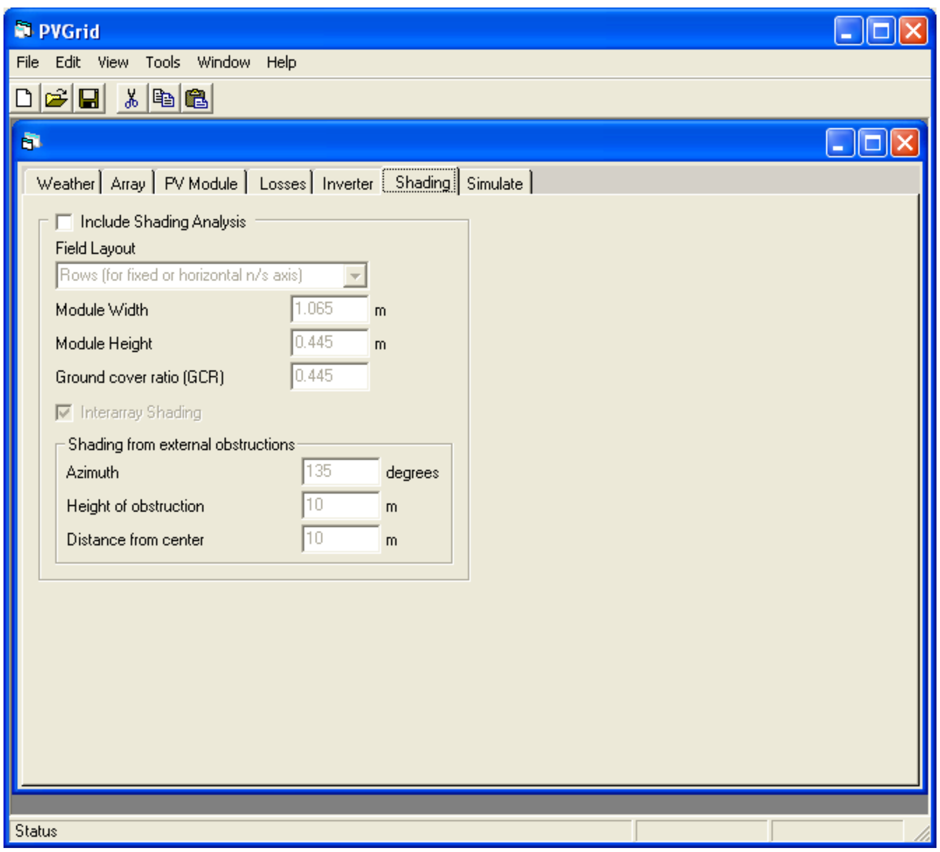

Figure 4-11. Screenshot of new features in Windows-based interface

Source: PowerLight Corporation

4.3.3 Software Validation

Table 12 shows the percentage difference between the expected energy production and the measured energy production at the five sites listed above. In general, the expected energy production matched the measured energy production very well. On an annual basis, the percentage difference was not more than 5%. Based on this data set, the authors did not find any correlation between location or latitude and the percentage difference. For example, one of the projects in Germany overperformed by 5%, while the other systems located in Germany performed 2 to 3% lower than predicted by the model.

Table 12. Annual percentage difference between measured energy production and PVGrid estimated energy production for five single-axis tracking sites, as measured during 2005

Project	Location	Latitude	System Size (kWp)	Annual % Difference (Performed-Predicted)
1	Muhlhausen, Germany	49.2	6,269	5%
2	Gunching, Germany	49.2	1,925	-3%
3	Minihof, Germany	48.5	1,890	-2%
4	Mesa, Arizona	33.3	243	-4%
5	Kona, Hawaii	20.0	209	4%

Source: PowerLight Corporation

The research team found that the percent difference in monthly power production was as high as 16%, as shown in Figure 4-12. There are several reasons for the larger discrepancy between actual and predicted output on a monthly basis. The most significant factors are system availability (affected by inverter outages and maintenance) and soiling. PVGrid currently models these effects by uniformly reducing the predicted output over the entire year; the research team applied loss factors of 2% and 5% for availability and soiling, respectively. In actuality, the effect of these factors varies in time. This time variance is evident when examined on a monthly basis, instead of an annual scale as specified in the model.

Two other important factors that affect PVGrid accuracy are the solar radiation measurement and the direct beam radiation calculation. The accuracy of the Licor pyranometer that measures the solar radiation is +/- 5%, while the Meteonorm's algorithm, which calculates the direct beam radiation, is accurate to +/- 8%. Since the expected energy production is highly dependent the amount of solar radiation measured at the site, it is very important to understand the accuracy of these sensors, especially when validating a new model. The research team calculated the uncertainty of the PVGrid predicted energy production to be 9.5%, while the uncertainty in the measured performance is 0.5%. The uncertainty in the ratio of actual to predicted performance, as plotted in Figure 4-12, is then 9.6%. As the difference between the measured PV and predicted production is at maximum 5% on an annual basis, the authors are confident in the validity of the model.

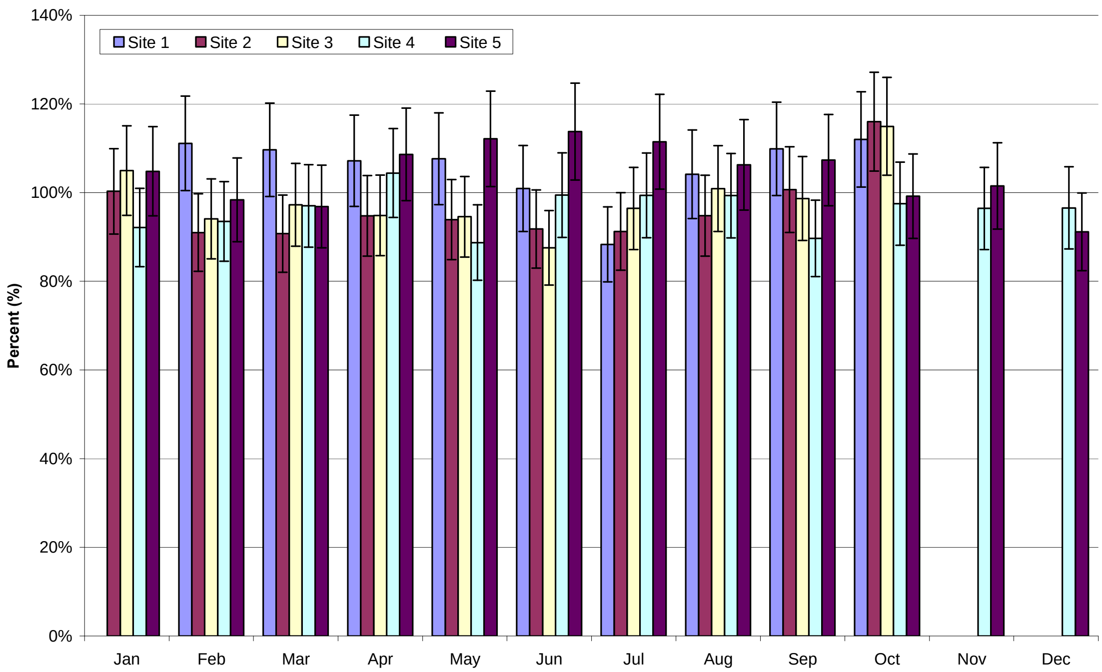

Figure 4-12. Measured monthly output as a percentage of predicted monthly output for five single-axis tracker sites.

Source: PowerLight Corporation

The results indicate that the modifications made to the PVGrid software are valid and accurately reflect measured data from operating single-axis tracking PV systems. This software tool will be used to aid in system design, as well as to estimate energy production.

4.3.4 Shading Analysis

Selection of GCR

PowerLight recognizes that many customers prefer to set the design based on: energy output, area available, and cost. Therefore, PowerLight selects a GCR appropriate for the parameter most important to the customer. This analysis is demonstrated in Figure 4-13, which shows GCR impact on project economics for a select group of cities in California.

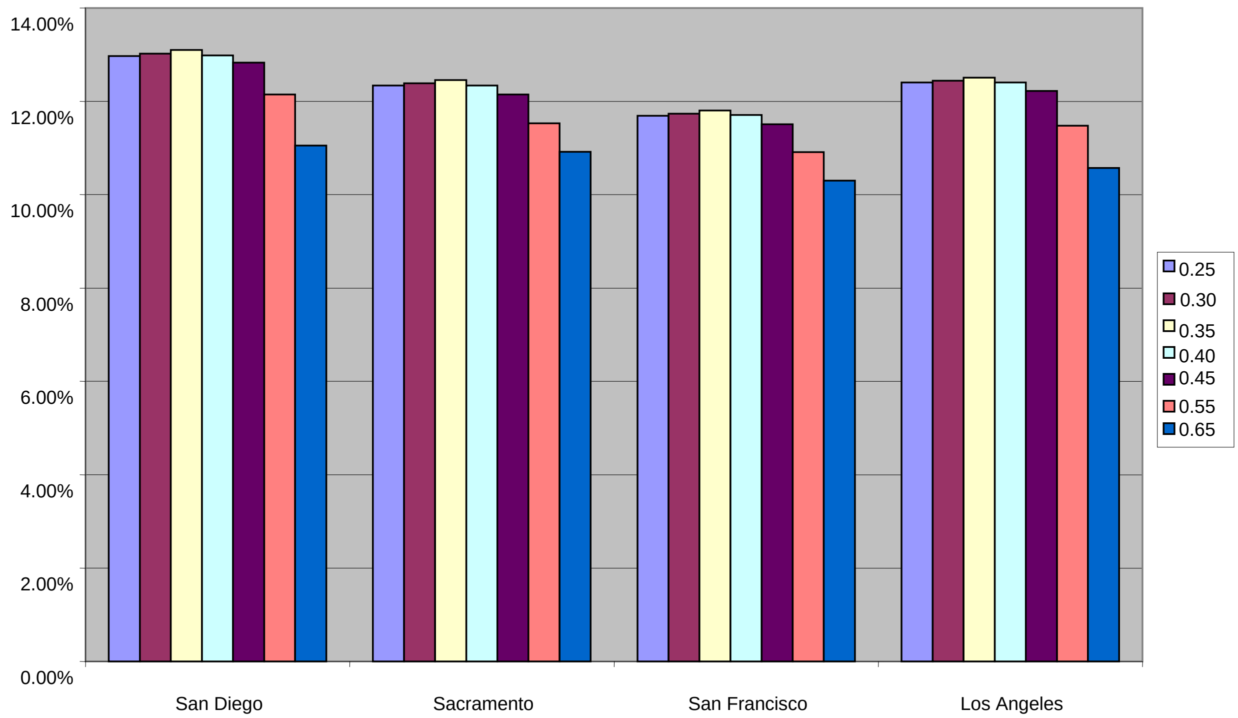

Figure 4-13. GCR impact on Customer IRR in select California cities

Source: PowerLight Corporation

For the authors' design purposes, an optimal GCR is defined as one with resulting energy loss less than 2%. As discussed below, the inter-array shading loss and required area are generally balanced at a GCR of 0.35. Depending on site-specific conditions, this GCR results in shading losses generally less than 2%, while the area required is reduced by 14% relative to a GCR of 0.30. In addition, this analysis shows that a single-axis tracker will have a significant energy increase over a flat or fixed tilt designs, across a wide range of latitudes.

Figure 4-14 and Figure 4-15 show the energy lost as compared to a "no shading" case at various GCRs for arrays installed in San Diego and Sacramento, respectively. These graphs were generated for each location listed in Table 13. The shape of the curve was similar for each location. Energy losses were larger at high GCRs, where the module spacing is closer. This loss began to flatten out around 0.40 GCR.

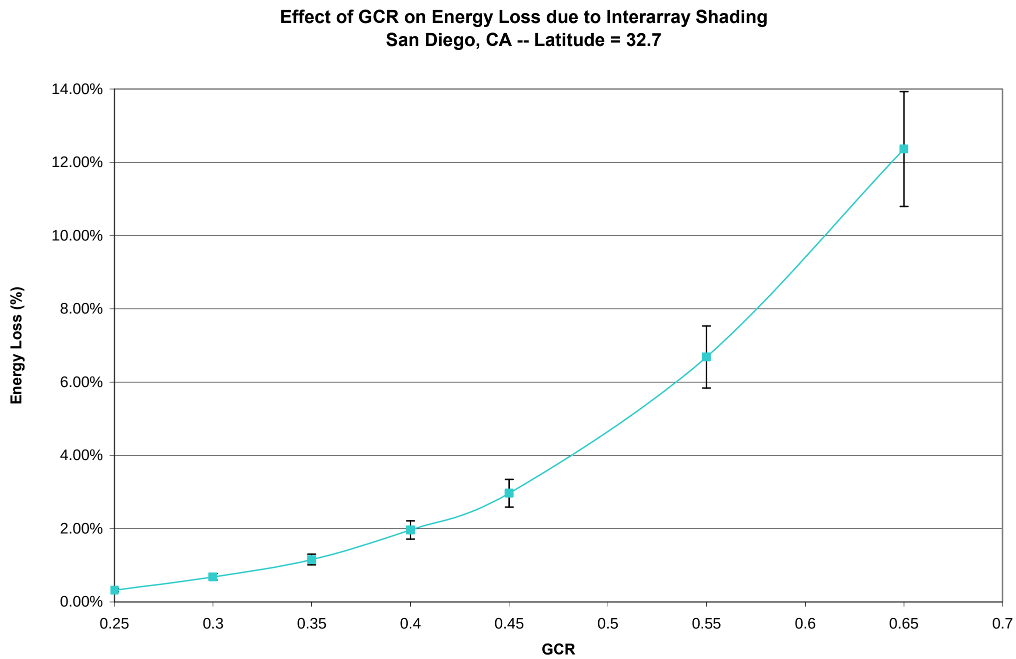

Figure 4-14. Energy loss for a single-axis tracker with various GCRs relative to "no shading" case.

Source: PowerLight Corporation

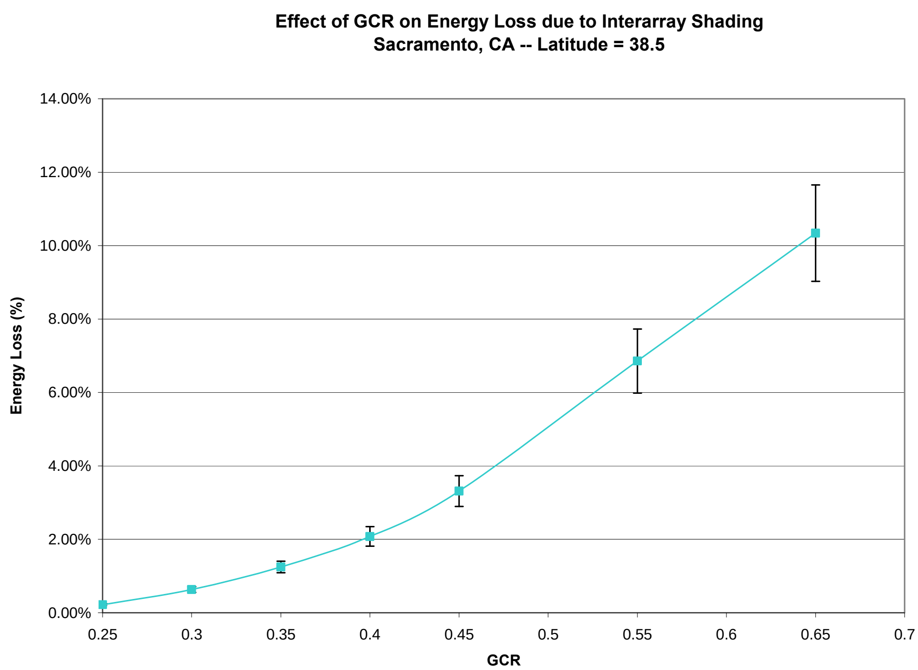

Figure 4-15. Energy loss for a single-axis tracker at various GCRs relative to no-shading case.

Source: PowerLight Corporation

The research team evaluated graphs generated for each location to determine the optimal GCR. For most locations, the research team determined that a GCR of 0.35 was considered optimal.

The system experiences shading losses generally less than the threshold of 2%, relative to the "no shading" case.

Decreasing GCR values to 0.25 results in minimal incremental energy gain for most locations. This spacing requires significantly more area (10-20%). By balancing the tradeoffs between energy production per square meter and shading losses, the authors have arrived at the optimal GCR values for each location (Table 13).

Table 13. Optimal GCR by location

Location	Latitude	GCR
Honolulu, HI	21.3	0.45
San Diego, CA	32.7	0.35
Los Angeles, CA	33.9	0.35
Las Vegas, NV	36.1	0.35
San Francisco, CA	37.6	0.35
Sacramento, CA	38.5	0.35
Beja, Portugal	38.0	0.30
Newark, NJ	40.7	0.35
Munich, Germany	48.2	0.30
Berlin, Germany	52.3	0.30

*Optimal GCR= energy loss less than 2%

Source: PowerLight Corporation

Figure 4-16 shows the effect of GCR on energy production and required area for an installation in Sacramento. As shown, a GCR of 0.35 produces approximately 0.6% less energy than an array with a GCR of 0.30, while requiring 14% less space.

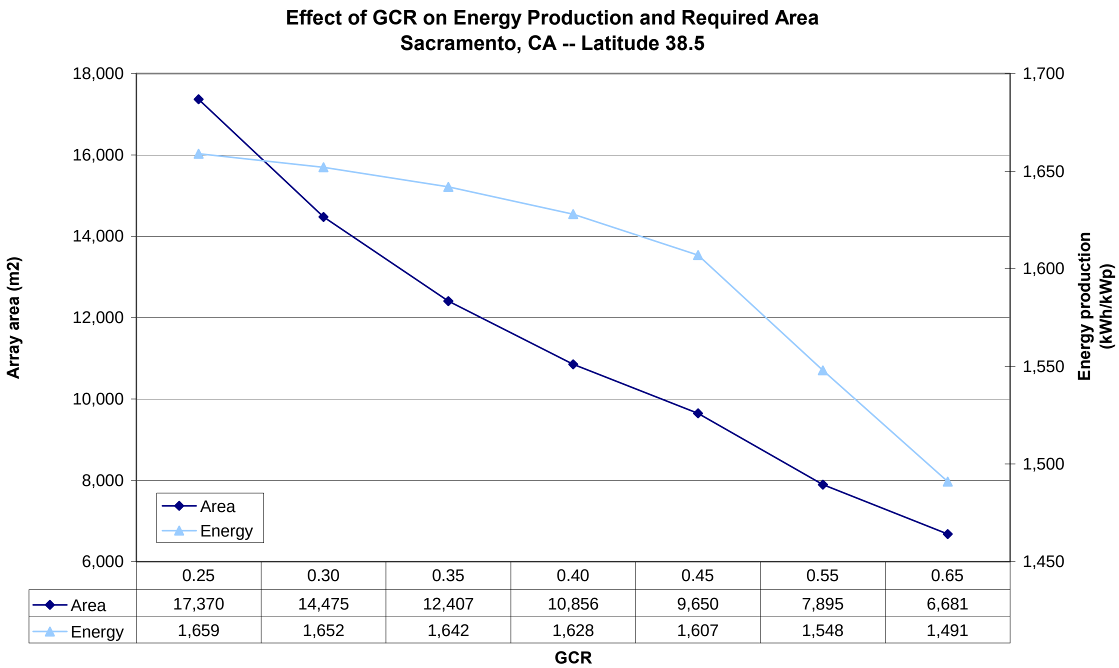

Figure 4-16. Effect of GCR on energy production and required area.

Source: PowerLight Corporation

This analysis provides the basis for selection of a GCR for a given site. System designer use these results to select a GCR that will yield high energy production with minimal shading losses.

Energy Performance versus Fixed and Flat Designs

The research team also used PVGrid to determine the energy gain of a single-axis tracker relative to a fixed-tilt and flat design. Figure 4-17 and Figure 4-18 show the results of this analysis. For the fixed-tilt design, the energy gain varied from 10% to 25%. For the flat-mount design, the energy gain varied from 18% to 36% depending on the location. Table 14 provides an example comparison of tracker performance relative to a fixed-tilt array located in Sacramento, California.

Table 14. Comparison of energy production for single-axis tracker and fixed-tilt arrays in Sacramento, California

Technology, GCR	Annual AC Energy Production (kWh/kWp)	Energy Production relative to Fixed-Tilt Array
Fixed tilt, 0.5 GCR	1368.4	100%
Tracker, 0.65 GCR	1,491	109%
Tracker, 0.55 GCR	1,548	113%
Tracker, 0.45 GCR	1,607	117%

Technology, GCR	Annual AC Energy Production (kWh/kWp)	Energy Production relative to Fixed-Tilt Array
Tracker, 0.40 GCR	1,628	119%
Tracker, 0.35 GCR	**1,642**	**120%**
Tracker, 0.30 GCR	1,652	121%
Tracker, 0.25 GCR	1,659	121%
Tracker, infinite GCR	1,662	121%

Source: PowerLight Corporation

As expected, the variation was very dependent on the amount of global and direct solar radiation. These results indicate that a single-axis tracker will have better performance and energy gain in locations with many sunny clear days. However, the energy gain of a single-axis tracker is still significant in climates that are generally considered to have a larger percentage of diffuse solar radiation, such as Germany and New Jersey.

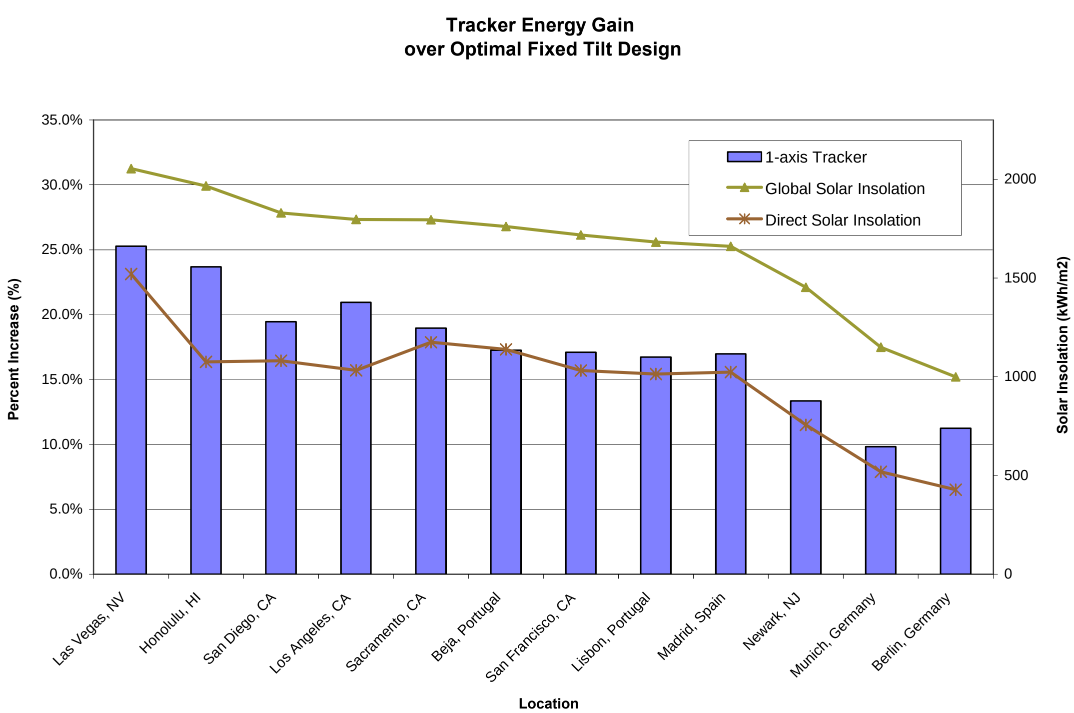

Figure 4-17. Energy gain achieved with a single-axis tracker relative to a fixed-tilt array design

Source: PowerLight Corporation

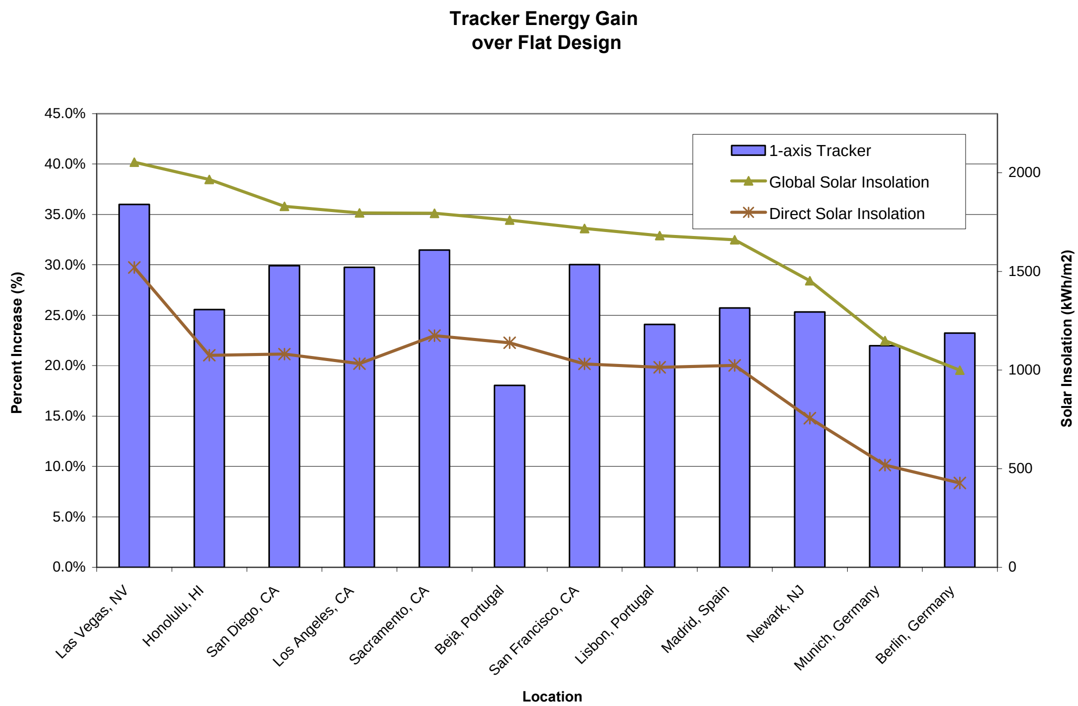

Figure 4-18. Energy gain achieved with a single-axis tracker relative to a flat array design

Source: PowerLight Corporation

The results of this analysis show that the GCR for a single-axis tracker can have a large impact on the energy generated. For most of the locations within the United States, we consider a 0.35 GCR optimal, as there generally is less than a 2% energy loss compared to the "no shading" case.

These software modifications allow PowerLight to accurately predict and compare energy production for various PowerTracker designs. The new software allows PowerLight to evaluate several designs and optimize the GCR to obtain greater system efficiency.

4.4 Task 4: Next Generation Structural Design

4.4.1 Wind and Structural Analysis

An extensive data analysis was conducted on the data collected in the wind tunnel for the seven configurations tested (See Table 1). Instantaneous lift, drag, and moment coefficients were calculated by integrating pressure data over the tributary area, which is dependent on feature evaluated. These coefficients were determined for all the instrumented PV modules throughout the array for each PV tilt angle and wind direction. Many of the PV modules were not instrumented, so load data for these modules was calculated by interpolation.

The worst-case drag, lift, and moments were identified for the particular configuration. Then, the distribution of the forces and moments throughout the array was studied so that the array could be divided into various wind zones: extreme wind zones around the perimeters of the array, and interior wind zones with lower wind loads.

Load diagrams were then created for individual PV modules, piers, and torque tubes. The same data was used to make the different load diagrams – the difference between them is that the tributary area for each component varies. For example, a pier feels the wind loads of nine PV modules, but a torque tube feels the wind load of an entire row of PV modules. When the tributary area is large, the wind load coefficients are smaller because worst-case loading does not occur at the same time over large areas.

Sample load diagrams are shown in Figure 4-19, Figure 4-20, and Figure 4-21. The load diagrams contain worst-case drag, lift, and moment coefficients for each particular configuration; this proprietary data has been removed for reporting purposes.

These load coefficients are then used in the following equations to calculate the drag and lift forces, and moments on components in actual arrays:

4.4.2 *PV Loads*

Corresponding Coefficients

X (horizontal) Force: $F_x = C_{F_x} qDC$ **(Eqn. 1)** $C_{F_x} = \dfrac{F_x}{qDC}$ **(Eqn. 2)**

Z (vertical) Force: $F_z = C_{F_z} qDC$ **(Eqn. 3)** $C_{F_z} = \dfrac{F_z}{qDC}$ **(Eqn. 4)**

Y (pitch) Moment: $M_y = C_{M_y} qDCL$ **(Eqn. 5)** $C_{M_y} = \dfrac{M_y}{qDCL}$ **(Eqn. 6)**

Where q is the hourly-mean dynamic wind pressure measured at 10 meters above the ground and is calculated using the ASCE-7 procedure outlined in Section 6.5 of the ASCE code, and D, C, and L are the representative dimensions of the PV module as defined by

D: width of the PV, that is 2.67 feet (32 inches),

C: chord length of the PV, that is 5.17 feet (62 inches), and

L: half the chord length of the PV, that is 2.58 feet (31 inches).

4.4.3 *Pier and Row Loads*

Corresponding Coefficients

X (horizontal) Force: $F_x = C_{F_x} qmDC$ **(Eqn. 7)** $C_{F_x} = \dfrac{F_x}{qmDC}$ **(Eqn. 8)**

Z (vertical) Force: $F_z = C_{F_z} qmDC$ **(Eqn. 9)** $C_{F_z} = \dfrac{F_z}{qmDC}$ **(Eqn. 10)**

Y (pitch) Moment: $M_y = C_{M_y} qmCDCL$ **(Eqn. 11)** $C_{M_y} = \dfrac{M_y}{qmCDCL}$ **(Eqn. 12)**

Where m is the number of PV modules supported by a pier or included in a row.

The load coefficients are defined by the above equations and are presented here to demonstrate the relationships among the variables. In the wind tunnel, forces and moments (F_x, F_z, and M_y) on the tracker model were measured by integrating the pressure data, which was collected during the tests, over the specified areas. The pressure data was collected from pitot tubes placed throughout the array. The hourly-mean dynamic wind pressure, q, was measured with a pitot tube upstream from the array.

Once the forces, moments, and pressure were measured, a data analysis was conducted to analytically determine worst-case load coefficients (C_{Fx}, C_{Fz}, and C_{My}) in various regions of the array. The analysis was based on the above equations.

Figure 4-19, Figure 4-20, and Figure 4-21 show the resulting load-zone diagrams, which give load coefficients for various locations in the array. For example, PV modules in outer regions of the array experience higher loads than interior modules. PowerLight's original report from the wind tunnel includes the actual values for load coefficients. The load coefficients for the various regions are being applied in the structural design of tracker projects. Since the numerical data is confidential, it is filtered for the purposes of this report.

As discussed above, lift, drag and moment coefficients were calculated based on the wind tunnel results. These values are then applied to the design of Tracker projects. A comparison between code-based calculations and wind tunnel-based calculations showed that for certain tracker configurations, the code-based approach yields lower forces. In other cases, the wind tunnel data suggested that wind loads were lower than the codes predict. This variation from the theoretical model and empirical data is expected, as discussed below.

Wind design standards are based on wind tunnel testing, In fact, much of the data provided in the American Society of Civil Engineers wind design standard (ASCE-7) was provided by the same wind tunnel that conducted the testing on PowerLight's tracker array.

Code-based calculations on the tracker system are based on the ASCE wind design standard for buildings. Specifically, the section on "partially enclosed, monoslope roofs" is used to approximate wind loads on the tracker. The tracker geometry is somewhat similar to this type of structure. However, although the code-based approach is accepted by professional engineers and building officials, a wind tunnel test on the specific tracker geometry is much more accurate. The wind engineering industry generally accepts wind tunnel testing on specific geometries as more accurate than code-based predictions because the code is generic in nature.

As such, this variation from the theoretical model and empirical data is expected. By augmenting and comparing the code and wind tunnel results, a more complete understanding of the forces on the system is formed. Melding these data sets prevents systems from being under designed or overdesigned. The code results serve as a starting point to understand the relative scale of forces on different members of the structure.

Because it is believed that the wind tunnel results provide a more accurate picture of wind-induced loads on the tracker, the wind tunnel results are being used to design tracker systems, even in cases where codes would predict lower loads. Deviations from code are expected, as code is applicable to buildings, beginning at heights of 15′ and ground-mounted PV systems differ significantly from buildings.

Application of Wind Tunnel Results to Commercial Projects

Using the load-zone diagrams (Figure 4-19, Figure 4-20, and Figure 4-21) as the generic case, project designers then superimpose the load zones on actual project layouts. For each load zone, A-D, the designer applies the calculated load coefficients to the structural design of the specific tracker project. Figure 4-22 shows an array layout overlaid with the load zones derived for a "pier load" scenario. After the wind loads are superimposed over the array, the designer then notes in which wind zone each pier is located. The load coefficients corresponding to each wind zone are then applied to the piers. The result of the analysis is the determination of the worst-case lift and drag forces on each pier. Structural engineers then use these loads to design the pier size and pier foundation specifications. Typically, it is undesirable to vary pier geometry, such as the wall thickness within one project because it is overly complicated to install. However, in many cases, the foundation design may vary for different pier loads. For example, the depth of the foundation is one part of the design that is easily varied in the field. In these cases, piers in high wind zones would have a deeper foundation than piers in moderate wind zones.

The wind tunnel studies completed under this task have improved the team's knowledge of the loads applied to tracker structures because accurate, worst-case design loads have been measured in the wind tunnel and incorporated into PowerLight's design process. This information has already been applied to two tracker projects, allowing the structure to be fine-tuned based on location within the array so that costs are minimized while structural integrity is ensured. With the size of PowerTracker systems growing to multiple megawatts, the ability to apply standard, optimized designs to various parts of the array can have significant effect on overall system cost.

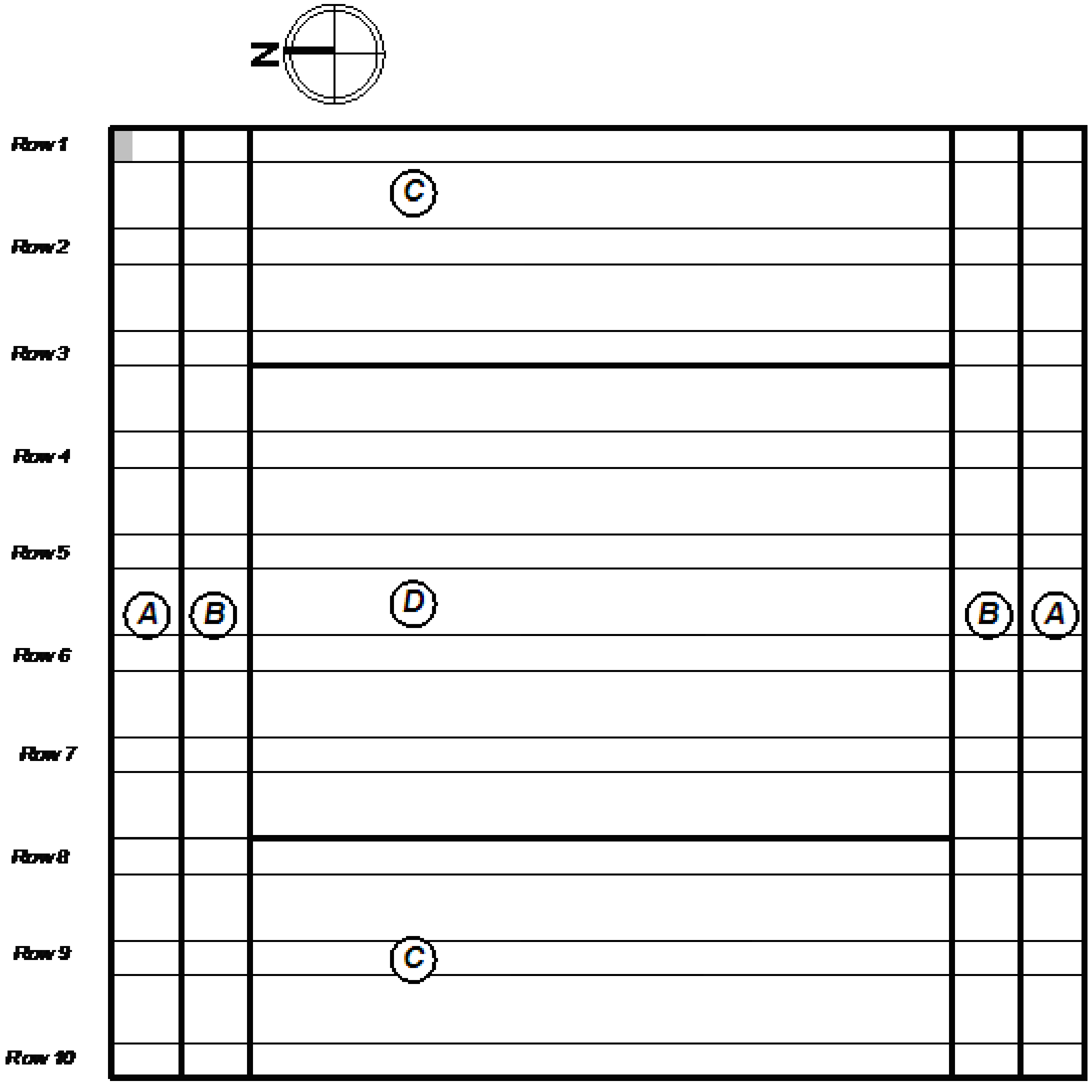

Figure 4-19. Sample PV load diagram. For each loading zone, A-D, lift (CFx), drag (CFz), and moment (CMy) coefficients were computed, based on measured pressure integrated over the PV area. For reference, a sample PV area has been highlighted above.

Source: PowerLight Corporation

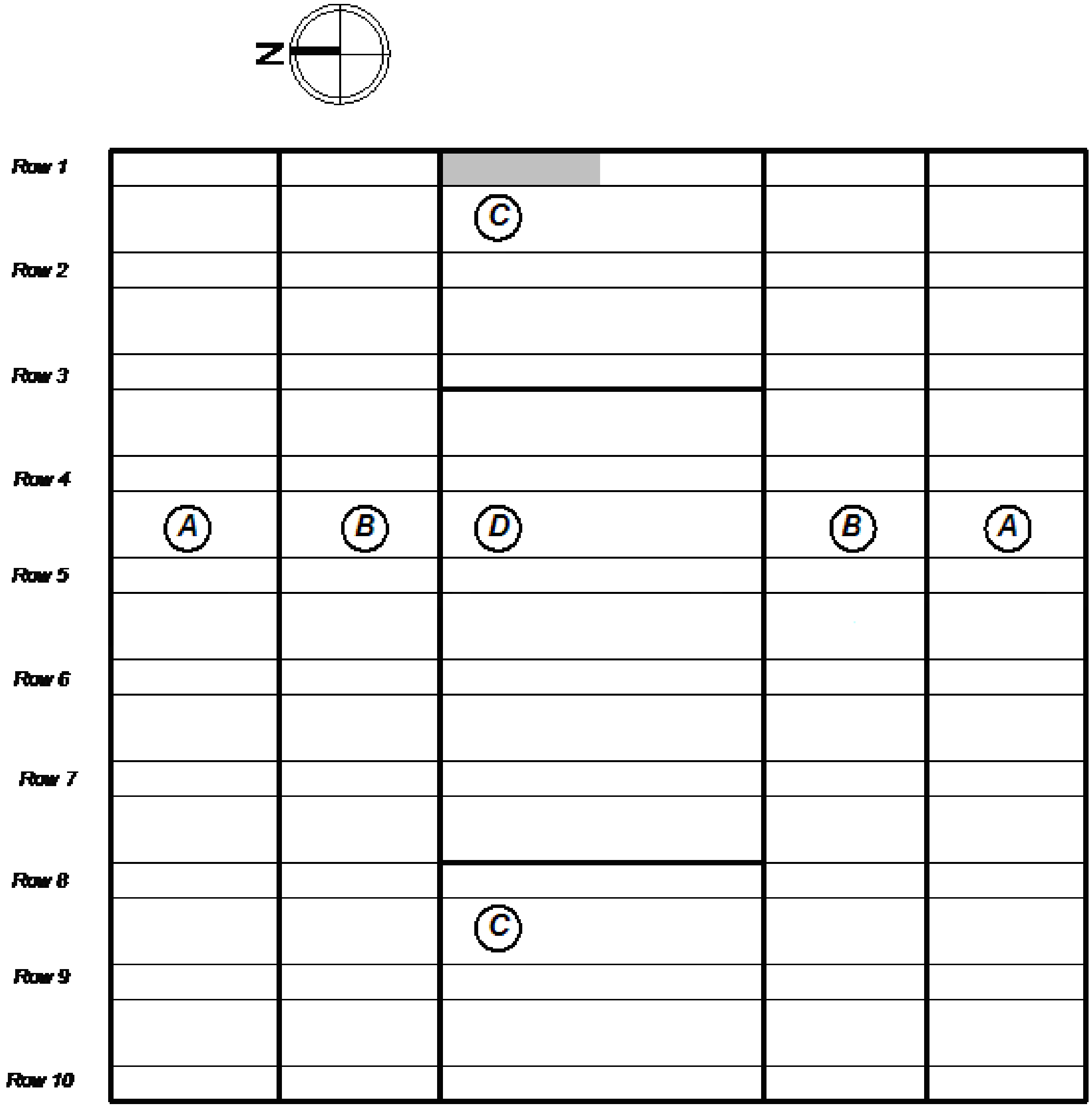

Figure 4-20: Sample pier loading diagram. For each loading zone, A-D, lift (CFx), drag (CFz), and moment (CMy) coefficients were computed, based on measured pressures integrated over the pier area. For reference, a sample pier area has been highlighted above.

Source: PowerLight Corporation

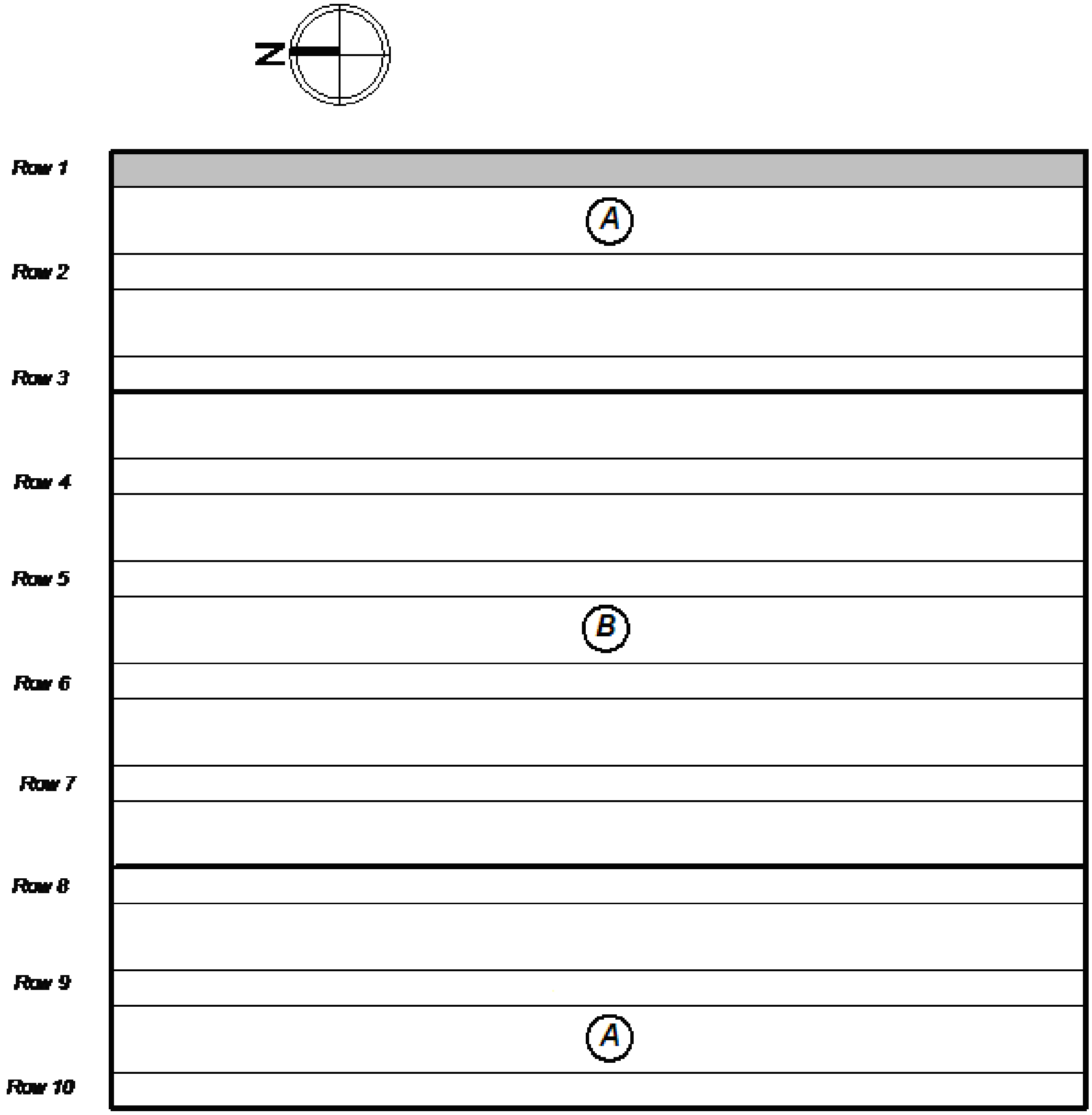

Figure 4-21: Sample torque tube load diagram. For each loading zone, A and B, the moment coefficient (CMy) was computed, based on measured pressures integrated over the row area. For reference, the area of Row 1 has been highlighted above.

Source: PowerLight Corporation

Figure 4-22. Sample Commercial Project with Loading Zones. The load zones determined from the wind tunnel results are superimposed over the actual project layouts.

Source: PowerLight Corporation

4.4.4 PV Mounting Hardware

Initially, the research team developed prototypes to mount IFF and EFF frames directly to the torque tube. These prototypes met the team's design requirements for applications in most regions. However, the authors' found that certain PV frames would require additional support in order to withstand extreme winds. While effective, most solutions resulted in a significant cost increase. The most promising solution involved adding more steel components to the PV frame, which added significant cost in raw materials and installation labor. The research team approached the PV module manufacturers with the idea of modifying the frame itself. The results of these discussions led to the development of two custom frame types unique to PowerLight, as shown in Figure 4-23. By altering the frames, the PV modules were now strong enough to withstand the most extreme wind and weather loading, while at the same time providing the necessary clearance to prevent mechanical interference. The authors could now use their preferred "center" mounting techniques without the use of the additional support channel. This solution helps minimize costs by decreasing custom engineering expenses. In addition, this option does not affect the standard PV warranties.

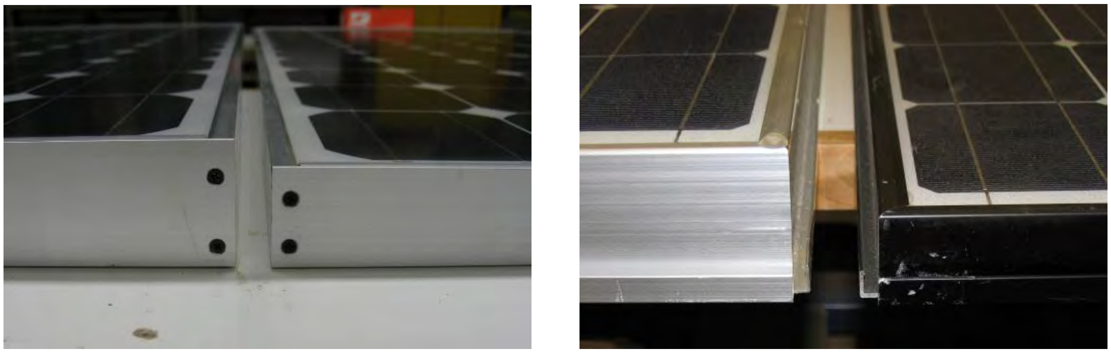

Figure 4-23. Comparison of customized PV frames with standard for (a) IFF and (b) EFF
Photo Credit: PowerLight Corporation

4.4.5 Materials

The PV frames are made of anodized aluminum for corrosion resistance, which is standard for the industry. This material holds up extremely well in all environments in which PowerLight has installed PV systems. For the IFF mounting hardware, the research team selected hot-dipped galvanized carbon steel for strength, cost, and corrosion protection. For external-flange frames, the research team selected stainless steel as the material. Both mounting clips have integrated features that ensure reliable grounding.
For the fasteners, the research team specified mechanically galvanized carbon steel hardware. Standard electroplated zinc and stainless steel hardware were also considered but were found to be less suitable. Electroplated zinc hardware does not provide the long-term corrosion resistance required of the PowerTracker system, while switching to stainless steel was cost-prohibitive.

4.4.6 Non-Tilted Design

IFF and EFF designs are shown in Figure 4-24.

Figure 4-24. Preliminary PV mounting hardware designs for (a) IFF and (b) EFF
Photo Credit: PowerLight Corporation

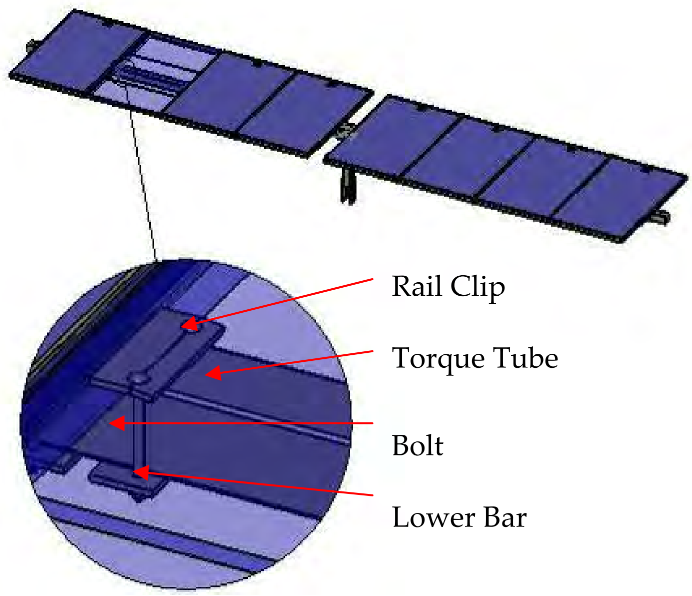

Figure 4-25. Rail clip assembly through the PV module for IFF

Source: PowerLight Corporation

Design Validation and finite element analysis

Due to the complex forces the rail clip is expected to experience, finite element analysis (FEA) was used to validate the strength of the hardware by finding the location and magnitude of stresses.

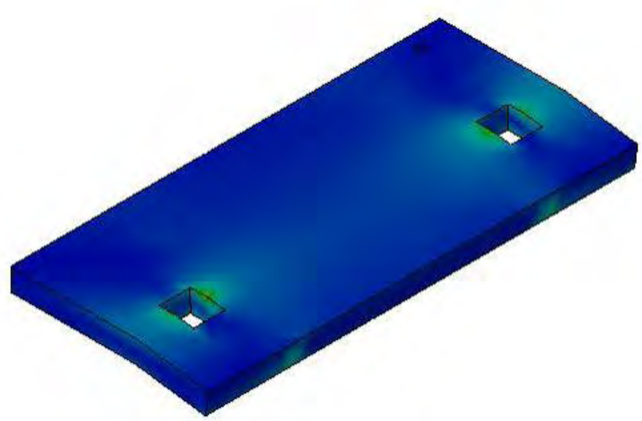

Figure 4-26. Stress distribution on IFF mounting hardware

Source: PowerLight Corporation

The forces applied to the clip result from bolt preload and wind loading. The bolt tension is calculated from the torque specification. The wind force is determined by applying a worst-case pressure distribution.

Figure 4-26 shows the expected stress distribution throughout the rail clip during a wind event. The forces applied to the clip in the analysis result from bolt preload and wind loading. The bolt tension applied is calculated from the torque specification. The wind force is determined by applying a worst-case pressure distribution.

It can be noted that the stress is primarily concentrated near the top of the carriage bolts and at the contact point with the torque tube. This relatively high stress is acceptable because the high stress is localized, and the FEA software is unable to simulate stress relief though yielding. As such, these results are thought to be conservative. Since the stresses on the part are almost entirely under the yield stress of the steel, the design is structurally sound.

Thermal and Corrosion Testing

The National Electric Code requires that all accessible conductive parts in a PV system be grounded to a common earth ground. Underwriters Laboratories requires that the resistance across grounded connections in a PV system be less than or equal to 100 m-Ohms. The conductive parts in the PowerTracker system have been shown to comply with these minimum requirements. However, there are no established industry standards that address the durability of the ground connections over time.

PV systems experience daily temperature cycling and exposure to potentially corrosive environments. To ensure that these environmental factors do not reduce the ground integrity of the PowerTracker system to unacceptable levels over the intended design life, PowerLight undertook a research and testing program. Research was conducted to determine if proven methods of creating reliable ground bonds existed in the utility and PV industries, and if standardized tests have been developed and applied to grounding systems for validation purposes.

Utility and PV experts were contacted to discuss the long-term durability of ground connections used outdoors. No information was found that specifically addresses the grounding of anodized aluminum parts to steel – it appears that the PV industry has a unique requirement to bond these two materials together electrically. Currently, PV frames are made of anodized aluminum, PV support structures are made of galvanized steel, and some PV mounting hardware is made of stainless steel.

There is no empirical or test data available to PV design engineers to ensure that grounds remain sound over the long term. Instead, the PV industry must rely on standard engineering principles. It is known that corrosion cannot occur without the presence of oxygen. When metal parts are clamped together tightly, a gas-tight connection is achieved, and corrosion between the two parts will not occur. Utilities commonly use bolted connections to connect galvanized steel components together to create an electrical ground. Utilities believe that if a good mechanical connection is maintained, then a good electrical connection is also maintained.

A test program was developed with the goal of evaluating the long-term durability of the mechanical and electrical connection between PV frames and the PowerTracker structure before and after thermal cycling. A test sample was fabricated as shown in Figure 4-27. The sample consisted of sections of aluminum PV frames connected to the galvanized steel torque tube using PowerLight's custom-designed galvanized steel mounting brackets.

Resistance between several points on the sample was measured before subjecting the sample to thermal cycling. The measurement points are shown in Figure 4-27. Additionally, the torque on each bolt was set to specifications. The sample was then placed in a temperature chamber and subjected to 200 thermal cycles between -18 C and 90 C. After 200 thermal cycles, the resistance measurements were repeated, and torques on the bolts were also measured. Torques were measured by turning the torque wrench in a clockwise direction (the direction that would tend to tighten the bolt) until resistance was achieved, and then slowly continuing past the point of resistance until motion occurred. The torque that was indicated on the torque wrench when motion occurred was recorded as the post-conditioned torque. Results of the testing are shown in Table 15 and Table 16Source: PowerLight Corporation

Table 16. The torque measurements show that torque was reduced by 5 to 20% after thermal cycling.

Results show very small changes in resistance after thermal cycling – in some cases resistance went up, while in others, the resistance went down. In all cases, resistance was well below the maximum acceptable value of 100 m-Ohms. The changes in resistance across grounded connections after thermal cycling are considered insignificant. The maximum resistance value that was measured, 0.95 m-Ohms, was still over 100 times lower than the maximum value of 100 m-Ohms.

The torque measured after thermal cycling is well above the required torque to maintain a tight connection. According to industry standards, a torque of 96 in-lb would be sufficient for the bolts. PowerLight specifies a higher torque of 240 in-lb. This torque value was derived experimentally: the torque causing yield was measured, and the specification for the torque is 70% of this value. PowerLight's approach has been to use the highest torque setting possible without damaging the materials, to ensure that a solid connection is maintained over time. The lowest torque that was measured following the conditioning was 200 in-lb, well above the minimum acceptable value of 96 in-lb. This is believed to be an acceptable result, especially considering that the temperatures used during the temperature cycling (-18 C to 90 C) are unlikely to occur in a given PowerTracker system.

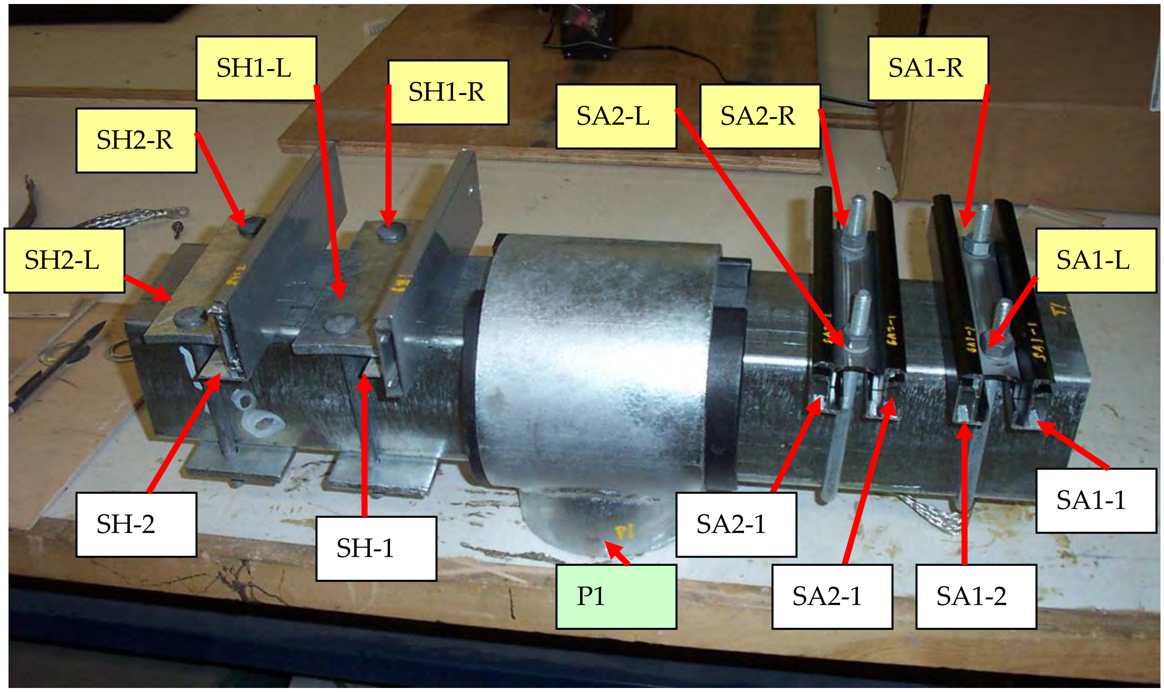

Figure 4-27. Test sample for thermal cycling tests. Resistance measurements were made between point P1 and points indicated by white boxes. The bolts, indicated by the yellow boxes, show where the torque measurements were made.

Photo Credit: PowerLight Corporation

Table 15. Resistance measurements (mΩ)

Point	Initial	After Cycling	Δ
SA1-1	0.58	0.65	0.07
SA1-2	0.64	0.7	0.06
SA2-1	0.83	0.95	0.12
SA2-2	0.49	0.39	-0.1
SH-1	0.48	0.53	0.05
SH-2	0.47	0.43	-0.04
P1	0.68	0.61	-0.07

Source: PowerLight Corporation

Table 16. Torque measurements (in-lb)

Bolt	Initial	After Cycling	Δ
SA1-L	240	200	40
SA1-R	240	225	15
SA2-L	240	200	40
SA2-R	240	200	40
SH1-L	240	215	25
SH1-R	240	225	15
SH2-L	240	220	20
SH2-R	240	230	10

Source: PowerLight Corporation

4.4.7 Tilted Design

In 2003, a PowerTracker system was installed with tilted PV modules by Arizona Public Service with materials supplied by PowerLight. This system employed a unique clamping mechanism as shown in Figure 4-28 and Figure 4-29 below.

Figure 4-28. Tilted PV Mounting Clamps

Photo Credit: PowerLight Corporation

Figure 4-29. Tilted PV Mounting Clamps Installed
Photo Credit: PowerLight Corporation

These clamps were designed specifically for the module used in this installation. Although sufficiently robust, the clamps were much more expensive to manufacture than standard "flat" mounting hardware. This was due to the custom welding required to fabricate these clamps. Thus, the benefits of the PV tilt were realized, but the cost was too high. The experience with this installation provided feedback crucial to further development of the product. Lessons learned from this project helped guide the next round of design concepts presented here.

North and South Clamps

The mounting used at the south side of each PV module is different from that used at the north side, as shown in Figure 4-30. In the northern hemisphere, modules are tilted to face south in order to increase energy capture; as such the mounting hardware on the north side of the module is taller in order to create the tilt. Since the PV module is touching the torque tube at the south end, the clip is very similar to that which we use with flat PV modules. The cost of this clip is similar to the standard tracker mounting clips.

The north end requires more material to elevate it relative to the southern end. Most of the associated cost of tilting the PV resides in this component. The concepts discussed here were expected to have costs well under the "threshold" of economic viability when produced in production quantities. However, on further analysis, this design did not provide sufficient energy benefit to offset the increased costs.

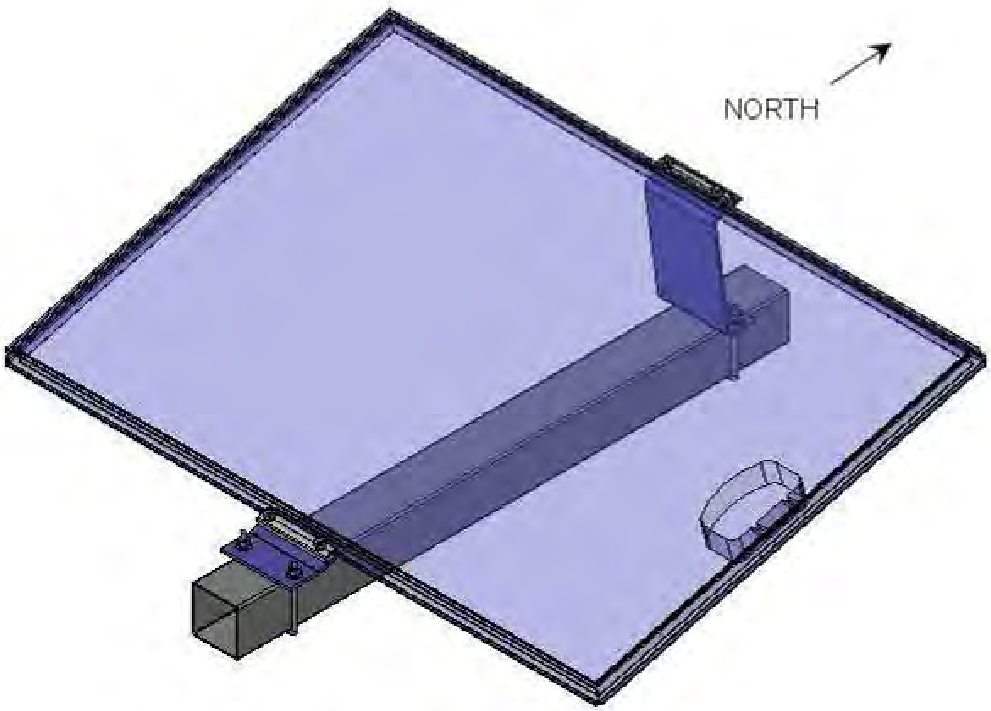

Figure 4-30. Tilted module assembly showing mounting hardware design

Source: PowerLight Corporation

Design Validation

Manual stress calculations were performed to validate the strength of the hardware by finding the location and magnitude of stresses. In this analysis, the research team considered the following potential failure mechanisms:

- North bracket failure in tension by bending.
- North bracket failure in compression by buckling.
- South bracket failure in compression by bending.
- South bracket failure in shear due by twisting.
- Bolt failure in tension.
- Assembly failure due to sliding down torque tube.

In all cases, the research team found the design to be adequate. The results from the corrosion and thermal testing, as discussed above, hold for these components.

4.4.8 Foundation Design

Drilled Piers

Drilled PowerTracker piers comprise a hole at least 15″ in diameter, a steel tube 4.5″ in diameter and deep enough to span from the base of the hole to at least 4′ above grade, and concrete to fill the hole around the steel tube. Figure 4-31 shows a typical drilled pier and the drilling process.

Figure 4-31. Typical drilled pier and drilling rig

Photo Credit: PowerLight Corporation

Design Methodology. PowerLight's first step in designing drilled pier foundations is to obtain a soils report and assess the bearing pressure of the soil and its friction coefficient. Next, the team estimated loading on the piers based on maximum wind speed conditions. The authors have extensive pier wind load data based on the wind tunnel testing carried out under this contract. Based on these loads, PowerLight designs the drilled piers by first selecting the maximum possible depth based on soil conditions, and then choosing a diameter that will prevent overturning. The formulae used to calculate overturning safety factors are based on Section 1806.8.2 of the 1997 Uniform Building Code (UBC).

Driven Piers

Driven piers comprise the same steel tubing used in drilled piers, but the tubing is driven directly into the ground without concrete. Based on a review of historical costs and conversations with qualified contractors, the authors believe it is possible to significantly reduce foundation costs by switching from drilled to driven piers. Furthermore, because the volume of concrete per project is significantly reduced, and because the embodied energy in concrete is high, driven piers also represent an opportunity to reduce total embodied energy for a solar system.

Design Methodology. PowerLight's first step in designing driven pier foundations is to obtain a soils report and assess the soil's rockiness, corrosivity, passive bearing pressure, and vertical friction coefficient. As a part of this Energy Commission contract, the authors have developed a set of criteria that can be used to evaluate whether or not a given soil profile is appropriate for driving piers. For example, soils that are too rocky are difficult to drive piers in accurately; soils that are highly corrosive will reduce the lifetime of the pier to a value below that of the PV modules; and soils with a low passive bearing pressure will not be able to withstand pier loads, especially given the relatively narrow profile of the pier, compared to a larger diameter drilled concrete pier.

If the soil type is considered appropriate for driven piers, the team follows the same UBC design methodology as with drilled piers, with the single exception of modifying the passive pressure multiplication factor to reflect the increased compaction of the soil that occurs when the piers are driven instead of drilled.

It is also worth noting that while driven piers save substantial cost by eliminating the drilling operation and immense volumes of concrete, there are other tradeoffs that offset some of these savings. The primary tradeoff results from the fact that the effective pressure bearing area of a driven pier is smaller than that for a drilled concrete pier of the same length. As a result, the driven pier must be set further in the ground for a given load, thus requiring incrementally more steel than the drilled equivalent.

High Efficiency Modules

Back-Contact Cell Modules. Mounting brackets were designed to accommodate the SunPower modules featuring high-efficiency, back-contact PV cells. This will allow the use of SunPower modules when there is sufficient supply for PowerTracker system needs.

The incorporation of SunPower modules will not have a significant cost impact on the hardware of the PowerTracker system. At present, the cost of the SunPower modules themselves is higher than other manufacturers, but this increase would be offset by the reduction in the number of modules that would be used to achieve a particular generating capacity and the commensurate decrease in the amount of structural hardware.

Bi-facial Module Characterization. The underside of the module was characterized and the performance closely resembled that of the top side. With the module suspended above the asphalt pavement and both sides exposed, a basic power output gain of between 4% and 20% was measured depending on the ground cover material, height of the PV, and tracker configuration. With the modules very close to a dark-colored surface at ground level, such as asphalt, the increase in output was measured at just over 4%. As the module was raised higher, the increase in output goes up until the height is above four feet. Beyond that, the increase stayed about the same. With a light-colored surface at ground level, such as white shiny plastic, the increase in output is measurably higher, well above a 20% increase, even with the module close to the ground. As the module was raised, the increase in output went up. However, since it might be difficult to maintain a shiny, light-colored surface under a tracker system, the research team has used more conservative level of increase that would result from a less shiny surface such as white concrete. For this reason, the team capped their estimate of the increase at 20% until they have better data from a large-scale system.

Table 17. Sample data for power increase resulting from use of bifacial modules

Mounting System	Test Configuration	% increase in power relative to module with back covered
PowerTracker System Module orientation: 0 degree tilt	Uncovered, 4' Above Bare Ground	5.87%
	Uncovered, 4' Above White Fabric	27.43%
	Uncovered, 18" Above White Fabric	27.31%
PowerTracker System Module orientation: 15 degree tilt	Uncovered, 4' Above Bare Ground	4.26%
	Uncovered, 4' Above White Fabric	18.77%
	Uncovered, 18" Above White Fabric	17.62%

Source: PowerLight Corporation

Irradiance on the Backside of Bifacial Modules

The test setup consisted of multiple irradiance measuring devices on a test module near the center of a commercial-scale array. Several of the sensors were located along the underside of the module along the center of its length. It addition, a meteorological station measured global horizontal irradiance, wind speed, and ambient temperature. A data logger was used to average and record measurements over 15-minute intervals. The irradiance under the PV was found to be fairly uniform. It was not significantly affected by the presence of cars. The irradiance was significant enough to produce a useful increase in power output. Testing did not include an evaluation of the impact of irradiance at the edge of the array; however, the edge effects are assumed to be negligible on full-scale installations. The consistency of the measurements over time confirmed the validity basing annual energy projections on the data collected at the Fremont site.

Energy Simulations of Bifacial Modules

The results of the research team energy simulations indicated significant energy benefit of the bifacial modules over time. The model predicted a range of improvement in module performance. PowerLight has plans to install a full-scale elevated tracker system using bi-facial modules. Monitoring of this system will confirm the predictions of annual energy capture on a large scale. This system is expected to be installed by mid 2007.

Bifacial PowerTracker Design Approach

The custom product being developed by PowerLight in partnership with one of the primary PV suppliers has a few unique advantages over conventional modules. The overall cost of the module is predicted to be comparable to standard PV cost when produced in large quantities. The materials are known to be comparable in cost to standard modules. The basic features of the bifacial module are as follows:

- **Double Glass:** Having glass on both the front and back of the module allows for superior weather resistance over time. The additional glass on the backside allows for excellent light transmittance, providing the maximum benefit of the bifacial cells.

- **Deep Frame:** The deeper frame profile creates a stronger frame, which allows for mounting methods that prevents shading of the backside of the module by the tracker structure.
- **Custom J-Box:** The junction box is traditionally placed directly on the back of the module. In this module, the box is integrated into the frame so that it does not block light to any of the cells.

Cost

One of the major advantages of the use of bifacial modules in the PowerTracker system is the fact that there is no significant increase in module cost. The cost of the modules themselves is expected to be very close to the cost of the standard modules using the same cells. This is based on feedback from the module supplier. The ability to increase output of the PowerTracker system without increasing cost will lead directly to lower system cost in terms of dollars per watt, which is the primary goal of this project.

4.5 Task 5: Documentation and Certification

4.5.1 Design Criteria

Under this project, PowerLight developed TrackerCalc, an MS-Excel spreadsheet developed to streamline the PowerTracker design process. This spreadsheet has two basic functions: structural design and bill of materials (BOM) creation.

Structural Design

The TrackerCalc spreadsheet requires the user to input three types of parameters to define the tracker structural design: site-dependent, pre-defined job-specific and designer-defined.

Site-dependent parameters are specific to the installation site and cannot be altered by the designer. The key site-dependent parameters are:

- Exposure category of surrounding terrain.
- Design wind speed (3-second gust)
- Parameters from the geotechnical report
- Estimated soil skin friction
- Estimated soil passive pressure
- Other soil characteristics, including depth of inactive soils and maximum drillable pier depth

These parameters dictate the structural design based on expected loads on PowerTracker components.

Pre-defined, job-specific parameters are attributes of the design that are typically determined before detailed structural design takes place. These parameters can be changed to suit the site characteristics, but are usually not adjusted to meet structural requirements before first adjusting the designer-defined parameters described below. The pre-defined parameters include:

- Module type
- Channel strut height, if present
- Module spacing
- Module gap over drive strut
- GCR (Ground Cover Ratio)
- Height of horizontal shear above grade (for bearing piers and drive pier)
- Load type (determines wind loading condition)

Module type is generally dependent on current supply, while spacing and GCR are functions of system size and performance expectations.

Designer-defined parameters include those that the designer can change manually to refine the design and those that can be automatically determined to optimize the design once all other parameters are set.

- Number of modules per row.
- Number piers/row.
- Distance between non-center piers.
- Max. number of rows per building block.
- Pier type.
- Drive unit position.

Based on these parameters, the TrackerCalc spreadsheet provides the designer with the following:

- Safety factors for all critical failure points in the structure
- Bearing and drive pier pipe wall thickness required to maintain acceptable safety factors.
- Bearing and drive pier diameter required to maintain acceptable safety factors.
- Bearing and drive pier depth required to maintain acceptable safety factors.
- Motor stall safety factor.
- Maximum PV load.
- Torque tube deflection when unloaded.

Using this output, the designer adjusts the design in order to ensure all design and safety requirements are met.

Bill of Materials

After completing the structural design process and array layout, the design can then create the project bill of materials (BOM), with the following parameters:

- PV module
- PV mounting hardware (depends exclusively on PV module type)
- Pier tubing wall thickness and length
- Square tube length
- Shroud, signage language, grounding parts
- Number of rows
- Number of heavy piers
- Specific part selection

Once these inputs are completed, the quantity fields for each part number are correctly populated. The resulting list of parts can be pasted into a separate sheet to be sent directly to the supply chain department.

4.5.2 Documentation Package

Installation Manual

In order that installation teams (mechanical and civil engineers, welders, electricians, and other subcontractors) are able to complete the installation, interconnection, and commissioning of a PowerTracker Solar Power System in a safe, thorough, and timely manner, PowerLight provides the PowerTracker Installation Manual to accompany the extensive drawing package created for each customer and system. This manual is the result of extensive knowledge sharing across all PowerLight divisions, as well as among organizations external to PowerLight whose experience with the product was also brought to bear during the creation of the manual.

Site visits, field research, and knowledge sharing accomplished the objective to assemble as much information and expertise as possible about the system itself as well as what the range of conditions regarding its installation could be, including:

- Precise photographic illustration of particular critical steps was achieved.
- Optimal flow of the most efficient, actual sequence of steps was arrived at.
- The goal of accumulating and then leveraging the largest possible body of knowledge and experience was achieved.
- The goal of identifying and eliminating redundancy and less-than-perfect procedures was achieved.
- The document has been field tested and has gone through several iterations in order to distill its contents down to what is required, what may be encountered, and how to mitigate the varying site conditions over the course of an installation.

The research team's work has yielded a valuable tool that will help facilitate rapid deployment of PowerTracker systems the world over. (The authors can translate the document when necessary.)

With this installation manual, The authors have achieved a comprehensive synthesis of the collective experience of true subject matter experts, in the form of construction managers, site supervisors, and subcontractors, as well as the individuals responsible for systems' operation, maintenance, and testing, and the authors have documented this knowledge in an intuitive format that is clear, concise, and comprehensive.

The PowerTracker System is a patented design incorporating a steel frame structure supporting rows of photovoltaic modules that are interconnected and controlled by a sophisticated, software-based drive unit. The system's single-axis design enables the modules to slowly move with the sun as it crosses the sky in order to maximize energy capture—the system automatically keeps the modules facing directly toward the sun.

PowerTracker's proven single-axis technology and precision engineering result in substantially increased sunlight collection—and significant reductions in the amount of land required to achieve this increase.

Unlike dual-axis systems that require wide array spacing, PowerTracker minimizes shading and thereby enables tighter spacing, typically requiring half the land area of dual-axis systems. PowerTracker incorporates GPS-based time and date measurements to accurately determine the location of the sun without light sensors or search algorithms. At low sun angles, PowerTracker employs its exclusive backtracking feature to prevent shading and to optimize energy production. In dual-axis systems, backtracking is generally much less effective and yields inconsistent results.

Operation and Maintenance Manual

The survey, analysis, meetings, and subsequent debate about how to best synthesize and present the information enabled a more accurate, real-world identification of the different audience categories, as well as yielding some very useful reference profiles of actual audience members.

From these definitions, the authors were able to further narrow the scope for each section, thereby enabling them to streamline the content, and structure it such that it remained consistent with the actual ways in which the target individuals would use the information in the field.

The research team optimized the following components of the operations, maintenance, and testing procedures:

- Tasks involved.
- Sequence in which the tasks were most effectively undertaken.
- Methodology used to execute the tasks.

The research team also re-categorized the information that was specific to the site/system owners, excising the text that was intended for those individuals that would instead be performing the maintenance.

In the end, representatives from all PowerLight internal divisions were unanimous in deciding to extract specific portions of the existing O&M manual in favor of eliminating it and instead creating two separate, standalone documents in its place: the Owner's Manual, and the Operation, Maintenance, and Testing Manual.

This pooling of product and installation knowledge, as well as lessons and experience from the field, enabled the team to leverage the perspectives of a multitude of individuals and arrive at a valuable and well-rounded consensus from which to base our documentation.

This work has resulted in the creation of two distinct manuals geared toward very different audiences, both rendered more effective by the retargeting. These documents will enable PowerLight system customers and service personnel to better comprehend their systems and to safely and properly execute any tasks related to the sustained, efficient operation of those systems.

The manuals represent a collaborative body of knowledge that reflects the most current practices and experience, and provide the audiences with an intuitive, easy to use reference for the operation, maintenance, and testing of their systems.

4.5.3 Certifications

The PowerTracker controller was tested for CE compliance at a third-party testing laboratory in California. Two major test categories were performed: safety and electromagnetic compatibility (EMC). Safety testing comprised application of high voltages, high currents, and tests for electrical isolation between major components of the system. EMC testing comprised primarily conducted emissions (i.e., through the power cable), and radiated emissions (i.e., through the air). The controller passed both tests, but several minor test-design iterations were required to achieve a passing result on the conducted emissions test.

4.6 Task 6: Next-Generation Electrical Design

The direct current (DC) portion of PowerTracker electrical systems suffered cost and maintenance issues in the past because standard methods of designing this element of the system were not established. In Task 6, the team successfully established standard methods of designing and installing the DC electrical components of the PowerTracker system. In doing so, the research team reduced the design and installation time of the systems and improved their overall aesthetics. Per combiner box, PowerLight realizes a savings of 37% per combiner box through the redesign effort, as shown in Table 18. During April 2005, a large-scale demonstration project was installed in Fremont, California, incorporating all of the improvements to the electrical system that were accomplished under this task. The demonstration system served to verify the efficacy of these improvements.

4.6.1 Module to Module Wire Routing

The photos shown in Figure 4-32 and Figure 4-33 demonstrates the clean aesthetics of the wire trays developed for elevated systems, as compared to the original wiring method employed on earlier tracker installations, as shown in Figure 4-32. These wire trays provide protection for the wires as well as creating a finished look for the system.

Figure 4-32. New components offer clean aesthetics for high profile systems, as demonstrated at this elevated tracker installation in Fremont, California

Photo Credit: PowerLight Corporation

Figure 4-32. Comparison of (a) improved wire trays with (b) original wiring method.

Photo Credit: PowerLight Corporation

Elevated structures are usually located in high profile public areas such as large business and government buildings, where the systems are subject to scrutiny by the public. The clean and safe design offered by these trays helps create a positive image of solar to the general public.

Figure 4-33. Summary of DC routing components developed under Task 6
Photo Credit: PowerLight Corporation

Figure 4-34. Standard module-to-module wire routing for ground mounted systems
Photo Credit: PowerLight Corporation

Figure 4-35. Original module-to-module wire routing for ground mounted systems
Photo Credit: PowerLight Corporation

For ground-mounted systems, the research team successfully installed commercial systems using the new module lead wire attachment specifications as shown in Figure 4-34**,** above. This solution offers easy, safe access to the module lead wires and adds to the professional look of the final installation, as compared to the original wiring method shown in Figure 4-35.

4.6.2 Row to Row (Homerun) Wiring

Row-to-row wire trays were selected that fit the functional and aesthetic requirements of elevated trackers. This tray is shown in Figure 4-33**,** Figure 4-36**,** and Figure 4-37.

Figure 4-36: Detail of transition and wire trays. Arrow indicates row-to-row wire tray.
Photo Credit: PowerLight Corporation

Figure 4-37: Detail of installed combiner box
Photo Credit: PowerLight Corporation

For ground-mounted systems, open wire trays were designed that reduce field labor and provide easy maintenance access. These are to be used specifically for systems that can only be accessed by qualified personnel. In such areas, where tampering is not a concern, these trays offer cost savings and a consistent method of routing the cables to the combiner boxes.

Using the test fixture, the authors were able to specify a method for running the DC conductors through the motion transition at each row. This flexible transition is shown in Figure 4-33 above. This method is being used on all new tracker systems.

4.6.3 System Grounding

PowerLight's cyclic testing of ground straps yielded a design that survived over 100 years worth of cycling. This design is shown in Figure 4-38.

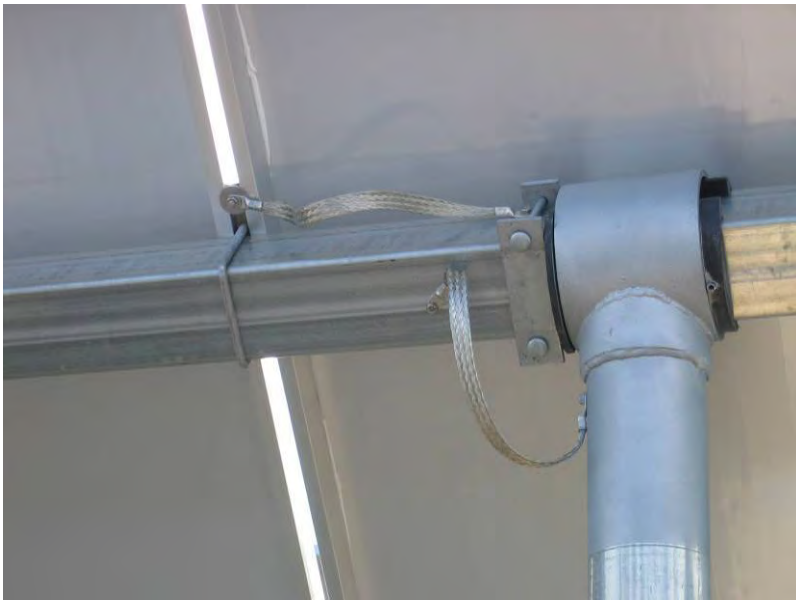

Figure 4-38: Standard ground braid designed for motion

Photo Credit: PowerLight Corporation

Standardized grounding methods were developed for the two types of PV frames described above. For frames with external flanges, a special clip was designed that will provide secure grounding of the module. For frames with internal flanges, the best solution was determined to be a standard specification for a braided ground wire and screw connections. By standardizing this hardware, all systems will be grounded in a consistent, proven manner, ensuring long-term safety of the system.

4.6.4 Combiner Boxes

The cost analysis for combiner boxes showed that the best solution incorporated the use of two sizes of combiner boxes: one for 35 strings applicable to the elevated-tracker system and one for 36 strings applicable to ground-mounted systems. The ground-mounted box was designed such that it can be installed on a small concrete pad adjacent to the tracker motor and controller. This strategic placement centralizes all electrical components, resulting in a central location for field maintenance and troubleshooting. The resulting combiner box, taking into account materials and labor, is 37% lower in cost relative to those installed prior to this project (Table 18).

Table 18: Relative Cost Reduction in Combiner Box Components

Component	Reduction
Cables	2%
Conduits	3%
Trenching	29%
Boxes/Hardware	3%
Total	37%

Source: PowerLight Corporation

These two boxes provide the flexibility of the small boxes yet avoid the unwieldy conduit routing concerns associated with the largest boxes. Figure 4-33 and Figure 4-37 show the new elevated tracker boxes in the commercial installation in Fremont, California.

The new boxes make better use of internal space through efficient arrangement of the components and allow mounting in either landscape or portrait orientation, depending on the physical constraints of the project. The new combiner box designs have successfully passed initial testing to UL 1741 standards. Certification was expected later in 2005.

In addition to the new combiner boxes, PowerLight developed a code-compliant method of using commercially available, fused disconnect switches for combining the output of multiple combiner boxes. This improves DC overcurrent protection, simplifies array maintenance, and enhances safety for maintenance crews.

4.6.5 Commercial Demonstration

In April 2005, PowerLight completed the installation of a 251-kWp elevated tracker in Fremont, California. This project included the improvements developed under Task 6 of this project. The experience gained during the installation of this system showed that the improvements are effective and meet the goals of improving cost and reliability. Photos of this system are shown in Figure 4-39 through Figure 4-42. Energy production for 2006 is shown in Figure 4-43.

Figure 4-39. Elevated tracker in Fremont, California
Photo Credit: PowerLight Corporation

Figure 4-40. Tracker control unit in Fremont, California
Photo Credit: PowerLight Corporation

Figure 4-41. Combiner box and conduit details of Fremont tracker
Photo Credit: PowerLight Corporation

Figure 4-42. Elevated tracker in Fremont, California
Photo Credit: PowerLight Corporation

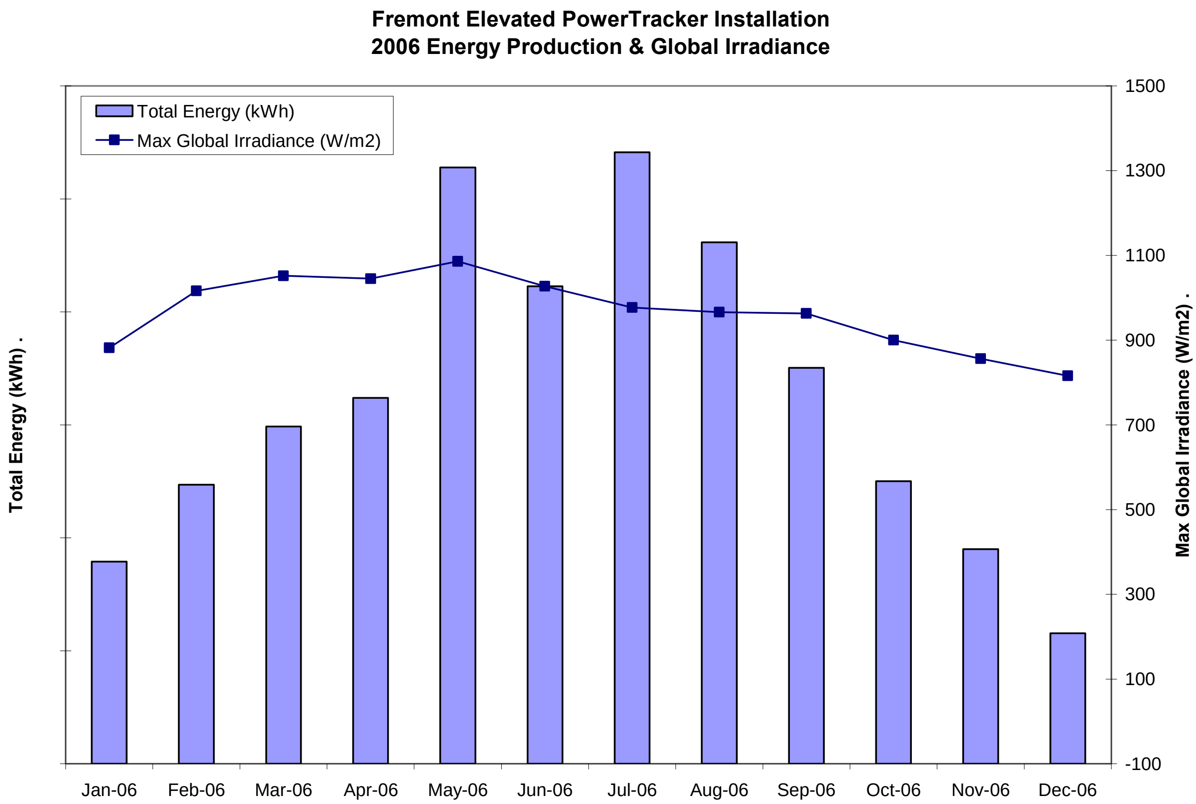

Figure 4-43. 2006 Energy production and global irradiance of elevated PowerTracker installation

5.0 Conclusions and Recommendations

5.1 Conclusions

This effort has improved single-axis PV tracking technology by increasing the quality while driving costs down, leading to the creation of more renewable options for California energy consumers. To achieve these goals, PowerLight adopted a holistic approach to product improvement. As such, this contract covered the full range of activities related to ground mounted solar tracking systems, including:

- The drive unit and controller.
- Tools for design automation and performance analysis.
- Tracker structural design.
- Documentation and product certifications.
- Electrical system design.

As a result of this contract, significant improvement in each of the targeted areas was achieved. A new controller design was implemented and has been deployed in the field with no reported reliability problems thus far. Improvements were made to PowerLight's performance analysis and design tools that resulted in reduction of the time required to analyze, design, and install individual PowerTracker projects by up to 58%. Important advances in structural design allowed lower cost and higher reliability trackers to be constructed, driven in part by new construction practices and a better understanding of wind loading. Based on current projects, PowerLight has achieved a 19% reduction in life cycle costs and anticipates an additional 10% savings due to decreased O&M expenses. In addition, PowerLight developed a new foundation design, resulting in a 20% reduction in steel waste streams for projects installed in 2006. Thorough and detailed product documentation has been extremely well received by system installers both inside and outside of PowerLight, providing the tangible benefit of standardizing installation practices and thus improving product consistency.

Overall, PowerLight believes that the work performed under this contract has been invaluable to the improvement of its solar tracking system, and that given the company's size and market share, a tangible benefit to the entire commercial solar power market has been achieved.

5.2 Commercialization Potential

PowerLight is moving forward with the commercial launch of this products with improvements developed under this contract. Large-scale commercial systems have already been installed at a customer's site. Many large California projects have been sold and are scheduled for installation in 2006 and beyond. Many large systems have been quoted to potential customers in a variety of locations in California, in other states, and overseas. Feedback from installers and potential customers has been very favorable.

5.3 Recommendations

5.3.1 Improved Tracking Geometries

Through the work performed under this contract, much has been learned about the performance of tracking solar power systems. PowerLight believes that PowerTracker is an excellent product for many applications, especially those where ground space is limited and thus a relatively high GCR is desired. As performance-based incentives come into play, PowerLight may need to investigate alternative geometries that provide better energy gain while leveraging the control, mounting, and actuation techniques developed for PowerTracker under this contract. Further leverage is also possible through the use of PowerLight's performance simulation tools.

5.3.2 Cost

Cost reduction will remain a high priority for all types of PV systems until they can compete with other forms of electricity production without buydown programs. It is a top priority for PowerLight to look continuously for ways to reduce the cost of this product as well as all of the others offered by the company. All aspects of ground based mounting systems must be examined on a periodic basis for ways to reduce the cost of materials, labor, and overhead.

5.4 Benefits to California

The achievements of this project provide many benefits to the state of California. The technical objectives set out at the beginning of this project have led to the improvement of a high-value PV product for large-scale commercial and utility applications.

At the start of this project, PowerLight had installed 760 kWp of the PowerTracker system worldwide, with no systems in California. Over the course of the project, PowerLight has installed or begun construction on over 4 MW in California and 38 MW worldwide. Improvements made to the PowerTracker technology have immediately been incorporated into the commercial product and will be utilized in the above projects. The next-generation PowerTracker, as developed under this project, will be deployed with an expected 29% reduction in life cycle costs.

In addition, PowerLight's employee base has grown significantly over the course of this project. At the start of the project, PowerLight had 84 employees. By the end of 2006, PowerLight has expanded to 184 employees in California and 194 worldwide. This growth has been fueled, in part, by the deployment of the PowerTracker technology.

Through funding assistance from the California Energy Commission's Public Interest Energy Research Program (PIER), PowerLight Corporation is making solar power more affordable. Solar-electric power systems provide a domestic source of energy that is plentiful, sustainable, and available throughout the United States. Photovoltaic (PV) systems transform clean, abundant solar energy into electricity, and are virtually maintenance-free.

Glossary

Acronym	Definition
CPR	Critical project review
DC	Direct current
DOS	Disk Operating System
O&M	Operation and maintenance
GPS	Global positioning system
GCR	Ground coverage ratio
kW	Kilowatt
MW	Megawatt
PV	Photovoltaic
PAC	Project Advisory Committee
PIER	Public Interest Energy Research
PLC	Programmable logic controller
VFD	Variable frequency drive
W	Watt